Exhibit 36

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Ammonia Emissions from Cattle Feeding Operations

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Issues and Emissions

Ammonia (NH_3) is a lighter-than-air, colorless gas with a recognizable pungent smell. It occurs naturally and is normally found in trace amounts in the atmosphere, where it is the dominant base, combining readily with acidic compounds. Ammonia is produced by the decomposition or fermentation of animal and plant matter containing nitrogen (N), including livestock manure, and is a source of the essential nutrient nitrogen for plants and animals. However, it is also classified as a hazardous substance by the US Environmental Protection Agency (EPA) due to concern about its potential to negatively affect air and water quality, and human and animal health.

Sources and emissions

Concentrated animal feeding operations (CAFOs) import feed ingredients that contain large quantities of nutrients such as nitrogen. Cattle retain a proportion of the nitrogen they consume, but approximately 70 to 90 percent is excreted in feces and urine (Cole et al., 2008). The breaking down of nitrogenous molecules in manure, such as urea and protein, produces ammonia. Urea in urine rapidly converts to ammonia and is a major ammonia source in manure, while microbes decompose more complex nitrogen-containing compounds, such as proteins, more slowly.

Historically, ammonia was considered a problem only within livestock buildings with inadequate ventilation or poor management.

Concentrated animal feeding operations import feed ingredients that contain large quantities of nitrogen. (Photo courtesy of S. Preece)

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High ammonia levels negatively affect animal health and production and threaten the health of humans working inside. Correcting ventilation problems and periodically removing animal waste reduces ammonia levels within buildings, but these measures do not address the problem of ammonia emissions in the atmosphere from open-lot CAFOs.

Ammonia begins to volatilize (convert to a gas and be lost to the atmosphere) almost immediately after urea is excreted. The loss can continue as manure is handled, stored, or land-applied as fertilizer. Nitrogen is an essential plant nutrient and a primary component of fertilizer; nitrogen lost to the atmosphere from manure by ammonia volatilization is a loss of fertilizer value.

Ammonia in the atmosphere eventually returns to the Earth and is deposited as gas, particulates, or in precipitation onto surfaces such as soil or water. Ammonia deposition on nutrient-starved farmlands may be beneficial to crops; however, deposition in sensitive areas may be undesirable.

The complexity of biological and chemical processes, coupled with management decisions, complicates the understanding of ammonia emissions from livestock operations. Differences in livestock digestive systems, diets fed, feed and manure management systems, facility design, location, and weather are just a few of the factors that affect ammonia sources and emissions.

Environmental concerns

Undesirable ammonia deposition occurs when air currents transfer ammonia to sensitive land and water surfaces. Dry deposition occurs locally, and wet deposition occurs at longer distances from the source. Ammonia deposition can harm sensitive ecosystems when excessive nitrogen stimulates too much algae growth in surface waters, or weeds in fields or pastures. When algae growth dies, its decomposition consumes oxygen, resulting in hypoxia (low oxygen) in aquatic environments. For example, the hypoxic "dead zone" near the mouth of the Mississippi River is caused by excess nitrogen and phosphorus carried by the river into shallow coastal waters. This process of eutrophication is characterized by significant reductions in water quality; a disruption of natural processes; imbalances in plant, fish, and animal populations; and a decline of biodiversity.

Sensitive terrestrial ecosystems may experience excessive weedy plant growth, which outcompetes more desirable native species (Todd et al., 2004). Ammonia deposited in soil can undergo nitrification, which converts ammonia to nitrate. Nitrate is mobile in water and the nitrification reaction lowers (acidifies) the soil pH (Myrold, 2005). Forests in the humid eastern United States are especially susceptible to soil acidification, which can cause winter injury, loss of tree vigor, and the decline of desirable species.

The National Atmospheric Deposition Program (NADP, 2007) and the Clean Air Status and Trends Network (CASTNET) are excellent sources of long-term deposition data. Multiple monitoring stations located in strategic areas across the United States monitor and document wet and dry deposition of ammonium, nitrates, and other pollutants. Data from NADP and CASTNET are available online at http://nadp.sws.uiuc.edu/ and http://www.epa.gov/castnet/.

Human health concerns

Ammonia can significantly contribute to reduced air quality when it reacts with sulfur dioxide or nitrogen dioxide in the atmosphere to form aerosols. Aerosols, also known as particulate matter, are atmospheric particles classified by the EPA according to their aerodynamic diameter. Respirable aerosols are particles that can be inhaled deep into the lungs and have a mean aerodynamic diameter of less than 2.5 micrometers ($PM_{2.5}$). $PM_{2.5}$ poses a threat to human health because it is associated with

Measuring ammonia emissions from concentrated animal feeding operations is difficult because ammonia quickly volatilizes and is dissipated by air currents. (Photo courtesy of S. Preece)

respiratory symptoms and diseases that lead to decreased lung function and, in severe cases, to premature death (EPA, 2009). Aerosols also affect cloud formation, alter the ozone layer, diminish irradiance, and reduce visibility in the air (Romanou et al., 2007; Chin et al., 2009).

Ammonia deposition can contaminate drinking water by increasing its nitrate concentration. This may occur by direct deposition onto water bodies or indirectly by leaching nitrogen from soils or by the erosion of nitrogen-laden soil particles into surface water.

Odor implications of ammonia are localized to regions in the vicinity of the CAFO. Ammonia is easily recognized by its smell, but is seldom associated with nuisance odor complaints near CAFOs any more than other manure constituents such as cresols, sulfides, or volatile fatty acids. Ammonia readily disperses from open-lot feedyards and dairies, which helps reduce its odor intensity to below human detection thresholds. Ammonia odors tend to be more noticeable inside animal barns than in open lots and are greater on or near CAFOs than at more distant off-site locations.

Measuring ammonia

Two categories of air quality measurements are commonly applied to ammonia at or near CAFOs: ambient concentrations and emission rates. Ambient concentrations are measurements of the ratio of ammonia to air in the atmosphere, usually measured in parts per million by volume (ppmv), parts per billion by volume (ppbv), or micrograms per cubic meter ($\mu g/m^3$). An accurate measurement of the atmospheric concentration in a large mass of dynamic, open air is difficult and requires special instrumentation and/or significant labor inputs.

Emission rates quantify ammonia flux from surfaces to the atmosphere and are reported in units of mass per unit area per unit time as in kilograms per square meter per day ($kg/m^2/day$), and also in units of mass per unit animal per unit time such as kilograms per thousand head per year (kg/1000 hd/yr). Measuring ammonia emissions from non-point sources such as CAFOs is also difficult because once produced, ammonia quickly volatilizes and is dissipated by air currents. Quantifying ammonia flux from the feedyard surface to the atmosphere relies on direct measurement using fast-response instrumentation or with a flux model, which attempts to predict accurately the dispersion of gases and particulates through turbulent air. Emissions will vary depending on the type of surface (buildings, lagoons, pens) and the nature of processes at individual facilities.

Regulatory issues

Federal reporting requirements (EPCRA)

Ammonia emission is regulated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Emergency Planning and Community Right-

To-Know Act (EPCRA). In December 2008, the EPA published a final rule that exempted CAFOs from reporting NH_3 emissions under CERCLA. However, under EPCRA [40 CFR §355 App A] CAFOs must report NH_3 emissions in excess of 45 kilograms (100 pounds) per day. Despite the challenges in accurately measuring ammonia emissions from CAFOs, an estimate of the lower and upper bounds can be calculated based upon animal headcounts and research-based figures for average emission rates per head. Non-compliance with the EPCRA NH_3 emission reporting requirements could result in fines of $37,500 per day, criminal charges, and up to five years imprisonment.

Ammonia emissions may be indirectly addressed by federal and state regulations aimed at $PM_{2.5}$ concentrations such as those in the National Air Quality Standards (NAAQS). Because ammonia is a precursor to $PM_{2.5}$, it may be necessary to reduce ammonia emissions in order to obtain a reduction in $PM_{2.5}$ concentrations. Currently, there are few state regulations directed at ammonia emissions from animal agriculture. In 2003, California's Senate Bill 700 removed the reporting exemption from agricultural sources and, in 2006, Idaho put into force their Permit By Rule program requiring dairy farms with the capacity to produce more than 100 tons of ammonia annually to comply. Excepting Idaho and California, existing state agricultural ammonia regulations are aimed primarily at the distribution, storage, and land application of anhydrous ammonia fertilizer. However, states can directly address ammonia emissions in $PM_{2.5}$ non-attainment areas in any case where ammonia is a significant contributor to $PM_{2.5}$ concentrations. Some states base general air quality regulations on atmospheric concentrations and other states base them on actual emissions similar to those stipulated by EPCRA. However, atmospheric concentrations and ambient emissions of pollutants like ammonia are not well correlated. How these existing air quality regulations will be applied to livestock ammonia sources in the future is unknown.

Ambient concentrations at cattle feedyards

Determining atmospheric concentrations of NH_3 requires sophisticated and expensive equipment, considerable labor, and much time. Measurements must be taken over large areas and during extended periods including all seasons to represent the large spatial and temporal variability. Other factors that must be reported include the animals, a detailed description of the facility, management practices, on-site weather, and sampling height. Data collected on atmospheric ammonia concentrations at CAFOs vary considerably, but tend to exhibit a 24-hour pattern, with daytime concentrations greater than those observed at night. Ammonia concentrations at cattle feedyards have rarely been observed over 3 ppm.

There are various methods for measuring atmospheric concentrations of ammonia, each with a unique set of advantages and disadvantages. Gas washing, denuders, and passive samplers provide average ammonia concentrations over relatively long periods of 1 to 4 hours. Gas washing is useful for calibration and standardization, but is labor-intensive. Fourier-transformed infrared (FTIR) spectroscopy, laser spectrometry, ultraviolet differential optical absorbance spectroscopy (UVDOAS), and chemiluminescence allow nearly real-time collection of measurements in relatively short periods of 5 seconds. Open-path lasers, UVDOAS, and FTIR have the added advantage of integrating measurements over distances from 50 to 500 meters. Because dust concentration in the vicinity of feedyards tends to be high, sampling for atmospheric ammonia requires special measures (such as installing Teflon filters preceding detectors or shortening measurement path lengths) to avoid errors.

Emission rates from cattle feedyards

An estimated 64 to 86 percent of total global anthropogenic (caused by human activity) ammonia emissions come from CAFOs (Baum and Ham, 2009; EPA, 2008; Becker and Graves, 2004; Battye et al., 1994). Of the CAFO emissions, roughly 43 to 48 percent come from cattle operations (EPA, 2008; NRC, 2003; Battye et al., 1994). Figure 1 shows the relative contributions to ammonia emissions made by various US sources based on the National Emissions Inventory (EPA, 2008). This inventory considered ammonia emission factors and county-level livestock populations (beef cattle, dairy cattle, ducks, geese, horses, poultry, sheep, and swine) intentionally reared for the production of food, fiber, or other goods or for the use of their labor.

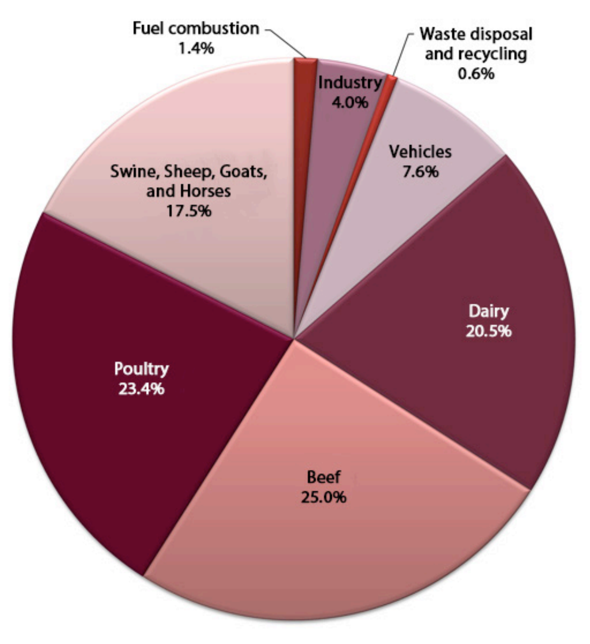

Figure 1. Estimated contributions of various US ammonia sources based on the National Emissions Inventory (EPA, 2008).

Extensive literature regarding ammonia emissions from swine and poultry facilities exists, but there is relatively little comprehensive research on large, open-lot beef cattle feedyards (Todd et al., 2008). Methods for estimating ammonia emissions from area sources such as feedyards include dispersion models, flux chambers, mass balance, micrometeorology, and wind tunnels (Hristov et al., 2011). The accuracy and applicability of these estimation methods varies greatly. For example, flux chambers and wind tunnels are appropriate for comparing treatments or assessing relative emission rates, but not for quantifying actual emissions (Cole et al., 2007; Paris et al., 2009; Parker et al., 2010). Dispersion models all rely on specific assumptions that are often challenged by the feedyard environment and can induce error in emission estimates (Flesch et al., 2005, 2007). Mass balance restraints are necessary to set an upper bound on emission estimates.

Calculating a total nitrogen balance for a facility involves determining the amount of nitrogen imported and exported from a feedyard and, assuming that unaccounted nitrogen is mostly ammonia, can provide reasonable estimates of ammonia emissions (Bierman et al., 1999; Farran et al., 2006; Cole and Todd, 2009). This is because the majority of gaseous nitrogen loss to the atmosphere is in the form of ammonia, as opposed to nitrous oxide (N_2O), nitrogen gas (N_2), or nitrous oxides (NO_X) (Todd et al., 2005). To minimize errors, compare estimates obtained by multiple methods with calculations from a complete nutrient balance and local atmospheric concentration data. However, this approach is site-specific and impractical for regulatory monitoring at every livestock operation.

Micrometeorological methods such as eddy covariance (EC) and relaxed eddy accumulation (REA) are ideal for feedlots because they provide measurements of ammonia flux for large areas without disturbing the emitting surface. EC involves high frequency measurements using a fast-response analyzer, accounting for vertical air movements and the mixing ratio of ammonia in the air. REA is an adaptation of EC in which samples from air moving vertically are accumulated over time and analyzed with slower-response analyzers.

The most common method regulatory agencies use to estimate ammonia emissions from CAFOs is to multiply a research-based emission factor by the number of animals on location. However, a single emission factor is not appropriate because ammonia emissions are affected by multiple, complex, and dynamic environmental variables. The National Research Council (NRC, 2003) has recommended a process-based modeling approach over the use of emission factors. Process-based models are based on the biological, chemical, and physical processes that contribute to emissions and take into account dynamic variables such as management practices, technologies, and weather conditions. Thus, they are applicable to a wide range of feedyard situations.

Research needs

Statistical, empirical, and process-based models estimate ammonia emissions from CAFOs. Statistical models are usually based on data collected from a particular location and provide estimates that may not be appropriate for a different site. Empirical models are commonly built from data collected under controlled conditions and predict well only when those particular conditions exist. Process-based (also known as mechanistic) models apply chemical and physical principles to a theoretical model of a real system, such as a CAFO. Their ability to predict ammonia emissions depends on how well the model represents real processes and the accuracy of important process factors used as inputs in the process-based model.

Many cross-disciplinary factors such as animal nutrition, environmental aspects, feedyard management strategies, and meteorological factors are considered in the construction of a process-based model. Process-based models of emissions from CAFOs often begin by describing the effects of diet and facility management on nutrient excretion by the animals. In the case of nitrogen, the various chemical forms, processes, and routes the nitrogenous molecules undergo as a feed constituent consumed and excreted by animals is described. Next, the nitrogenous manure constituents are accounted for and partitioned into several pools. Depending on the facility, these pools may include effluent lagoons, feces, manure stockpiles, pen surfaces, urine, and so forth. Finally, the chemical and physical transformations, transfer, and equilibria that occur during manure storage, handling, treatment, and export in each of the several cases are modeled. The model may then be used to predict ammonia emissions.

Models must consider atmospheric ammonia phases, which include gaseous ammonia (NH_3), fine particulate ammonia ($(NH_4)_2SO_4$ and NH_4NO_3), and liquid ammonia (NH_4OH) as clouds or fog. The transition between these three phases depends on other inconstant atmospheric constituents and the proportion of the phases relative to one another is also continually changing. Ammonia readily forms strong hydrogen bonds with water and will attach to many surfaces. Most materials exposed to air containing ammonia will absorb or adsorb ammonia compounds. In a CAFO environment, gaseous ammonia is prevalent and attaches to the airborne particulate matter emitted from the facility.

The dynamic nature of the atmosphere and its constituents results in significant variations in ammonia concentrations with respect to height

There is relatively little data on ammonia emission rates, emission factors, or flux rates from open-lot beef cattle facilities. (Photo courtesy of S. Preece) above the ground, location, and time. Increasing the distance from the emission source can decrease ammonia concentrations, with the rate of decrease depending on other factors such as air temperature, relative humidity, or wind speed. Dry deposition rates close to the CAFO can also decrease with respect to distance and range widely depending on atmospheric conditions and emission rates.

Measuring emissions

It is difficult to measure ammonia emission rates from open-lot CAFOs. Ammonia tends to collect inside sampling instruments, adversely affecting measurement. Because open-lot CAFOs have lower ammonia concentrations than those typical of facilities with livestock housing, measuring emissions requires more sensitive instrumentation. There is relatively little data on ammonia emission rates, emission factors, or flux rates from open-lot beef cattle facilities.

Despite sampling challenges, changeability of ammonia concentrations, and scarcity of data, the average daily ammonia concentrations observed at several facilities by different researchers are consistent (Table 1).

When estimating ammonia emissions from open-lot beef cattle facilities, several components of the CAFO system must be considered. Emission factors fail to account for the effects of particular components included in process-based models such as air and surface temperatures, animal age and diet, geographic location, time of year, and many others. So many variable and interactive system components must be considered that using a single emission factor is not adequate to predict ammonia emission rates (Hristov et al., 2011).

Processed-based models, which describe physical processes mathematically as opposed to statistically, are better suited to this task than emission factors. A single ammonia emission factor based primarily on European data proposed by the EPA (2005) is 13 kg/hd annually for feedlot cattle or 23 percent of the total amount of imported nitrogen. This EPA report also estimates the following nitrogen losses as ammonia: 1) stockpiles, 20 percent of nitrogen entering, 2) storage ponds, 43 percent, and 3) land application, 17 to 20 percent. Because European beef systems vary greatly from US systems, these values may not apply to US feedlot systems.

Studies conducted at North American feedyards using a variety of measurement methods observed a wide range of emission and flux (quantity per unit area per unit time) rates. Reported emission factors ranged between 18

Table 1. Ammonia concentrations (ug/m3) measured at several commercial open-lot beef cattle feedyards. (Adapted from Hristov et al., 2011.)

STUDY	TIME	LOCATION	MEAN or RANGE
Hutchinson et al., 1982	April–July	Colorado	290–1,200
McGinn et al., 2003	May	Canada	66–503
	July		155–1,488
Todd et al., 2005	Summer	Texas	90–890
	Winter		10–250
Baek et al., 2006	Summer	Texas	908
	Winter		107
McGinn et al., 2007	June–October	Canada	46–1,730

to 104 kg/hd annually, and flux rates ranged from 3.6 to 88 μg/m²/s. Most studies also noted seasonal or 24-hour patterns in ammonia flux rates (Hristov et al., 2011). Reported losses from runoff holding ponds ranged from 3 to 70 percent of the nitrogen entering the pond. Compost piles, another source of ammonia loss on beef cattle feedyards, have been estimated to lose 10 to 45 percent of their initial nitrogen content (Hristov et al., 2011).

Abatement Measures

Ammonia abatement measures can be implemented at two different stages of livestock production. First-stage measures are applied pre-excretion and include nutrition-based strategies to reduce the amount of nitrogen excreted in livestock manure. Second-stage measures occur post-excretion and use management strategies to reduce the amount of ammonia transferred to the environment from the manure at agricultural operations.

Nutritional ammonia abatement methods

One means of reducing ammonia emissions from CAFOs is to reduce the amount of nitrogen excreted by the animals, especially the quantity excreted as urea in urine. Urinary pH can also affect ammonia emissions (Cole et al., 2008a). In some cases, it is possible to manipulate nutritional intake to reduce total nitrogen and urinary nitrogen excretion while continuing to meet the nutritional requirements and performance expectations of the animals. Based upon consistent observations among researchers over the past decade, annual ammonia losses from beef cattle feedyards tend to be approximately half of the nitrogen consumed by cattle, and summer emission rates are about twice those in winter (Todd et al., 2009) (Fig. 2).

There are a variety of ways to modify ration composition to reduce ammonia emissions by 20 to 50 percent with only small effects on animal performance (Cole et al., 2005, 2006a; Todd et al., 2006). Nutritional factors that can be manipulated include cation-anion balance (CAB), crude protein and/or degradable intake protein concentrations (including phase feeding), fat concentration, and fiber source and concentration, as well as some growth-promoting feed additives and implants. However, the large size of many CAFOs presents economic and logistic challenges when modifying diets or feeding practices. Modifications to diets, equipment,

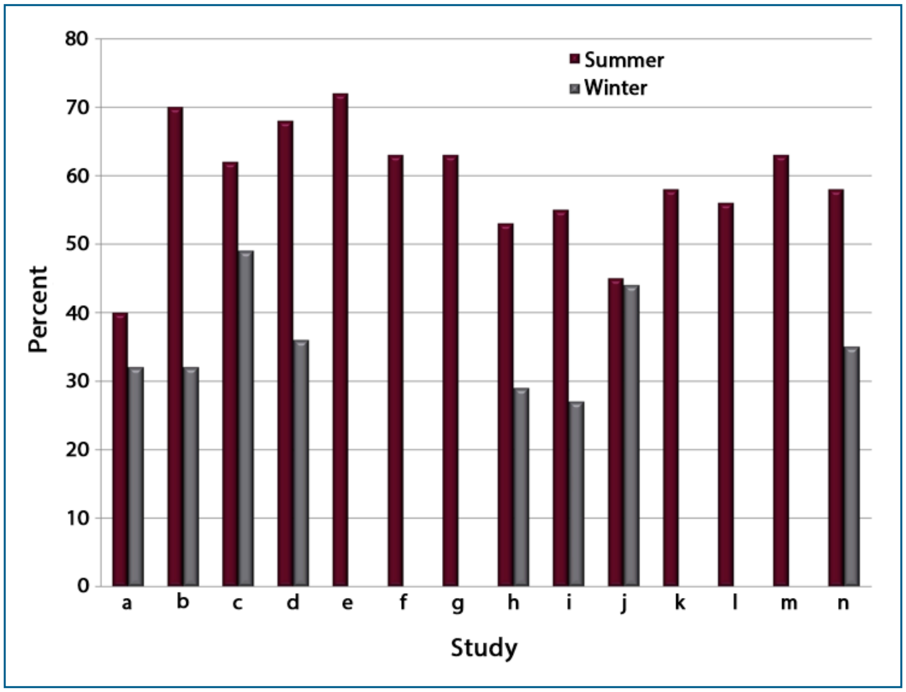

Figure 2: Ammonia-N loss as a percentage of fed nitrogen from Great Plains beef cattle feedyards. Studies: (a) Todd and Cole, unpublished data, (b) Todd and Cole, unpublished data, (c) Todd et al., 2011, (d) Todd et al., 2008, (e) van Haarlem et al., 2008, (f) McGinn et al., 2007, (g) Flesch et al., 2007, (h) Harper et al., 2007, (i) Todd et al., 2005, (j) Todd et al., 2005, (k) Cole et al., 2006a, (l) Erickson and Klopfenstein, 2004, (m) Erickson et al., 2000, (n) Bierman et al., 1999.

or management practices may impose increased cost, labor, and time.

Crude protein

The concentration of protein in feed, as well as its ability to be degraded in the rumen, may affect the quantity and route of nitrogen excretion by beef cattle (Cole et al., 2005). Beef cattle consume dietary crude protein in two forms: degradable intake protein (DIP) and undegradable intake protein (UIP). Microbes process DIP in the rumen where it is either absorbed (normally as ammonia) or converted to microbial protein and nucleic acids. UIP escapes digestion in the rumen and passes to the intestine where it is digested and absorbed as amino acids (approximately 80 percent) or excreted (approximately 20 percent).

In general, as nitrogen consumption increases, urinary nitrogen excretion also increases. As the ratio of DIP to UIP increases, urinary nitrogen excretion also increases. Dietary changes must be made carefully and with consideration to unintended consequences. For example, in attempting to lower ammonia emissions, if the dietary protein intake is reduced below the animal's nutritional needs, the growth rate may be slowed, the animal will require more days on feed to reach market weight, and the cumulative ammonia emissions from a feedlot may actually increase. Making changes to decrease ammonia emissions may potentially result in increasing other undesirable emissions such as nitrous oxide.

In closed chamber laboratory (Cole et al., 2005) and artificial pen surface (Todd et al., 2006) experiments, decreasing the crude protein concentration of beef cattle finishing diets based upon steam-flaked corn from 13 to 11.5 percent decreased ammonia emissions by 30 to 44 percent. Ammonia fluxes from an artificial feedyard surface were reduced by 30 percent in summer, 52 percent in autumn, 29 percent in spring, and 0 percent in winter (Todd et al., 2006). The research team concluded that despite requirements to maintain cattle performance, reducing crude protein in beef cattle diets might be the most practical and cost-effective way to reduce ammonia emissions from feedyards. Another study by Todd et al. (2009) determined that feeding high concentrations (greater than 20 percent) of wet distillers grains, which are becoming increasingly available as a ration component, increased crude protein intake in beef cattle and resulted in increased ammonia emissions.

Phase feeding

As beef cattle mature, they require less dietary protein. Phase feeding involves adjusting nutrient intake over time to match the animal's changing needs. If protein is not progressively diminished in balance with the animals' nutritional requirements through the feeding period, potentially more nitrogen is excreted and more ammonia may be emitted from the facility (Cole et al., 2006a; Vasconcelso et al., 2009). Studies on cattle fed high-concentrate, steam-flaked, corn-based diets have suggested that a moderate reduction (approximately 1.5 percent) in dietary crude protein (CP) in the final 28 to 56 days of the feeding period may decrease ammonia emissions by as much as 25 percent with little adverse effect on animal performance (Cole et al., 2006a). Based on seven cooperative studies to determine the effect of crude protein on ammonia emissions and animal performance (Cole, 2006b), a reduction of dietary crude protein from 13 percent, which is optimal for growth, to 11.5 percent resulted in a 3.5 percent decrease in average daily gain and an approximate 30 percent reduction in ammonia emissions. In certain economic conditions, it may be practical to accomplish a significant reduction in ammonia emissions with a minimal effect on animal performance.

Distillers grains

Distillers grains have recently been introduced into beef cattle rations and may affect CAFO ammonia emissions. Research by Cole

Frequent pen cleaning may help capture nitrogen in the manure and decrease losses to the atmosphere. A Nebraska study revealed that cleaning pens once a month instead of after every five-month feeding period reduced apparent ammonia losses by 24 percent and increased the nitrogen content in the manure by 50 percent. (Photo courtesy of S. Preece)

et al. (2008b) reported that a 10 percent increase in distillers grains in rations based upon steam-flaked corn increased manure production by approximately 10 percent. In rations based upon dry-rolled corn, the same increase in distillers grains resulted in a 0 to 7 percent increase in manure production. In both cases, the concentration of nitrogen in the manure was not affected. The combination of increased manure volume and steady nitrogen concentrations may result in potentially greater ammonia emissions. In a comparison of ammonia emissions at two feedyards, Todd et al. (2009) found that one feedyard feeding distillers grains averaged 149 grams of ammonia-N per head per day (NH_3-N head^{-1} d^{-1}) over nine months, compared with 82 g NH_3-N head^{-1} d^{-1} at another feedyard feeding lower protein steam-flaked, corn-based diets.

Fiber

Manipulation of dietary fiber may also affect ammonia emissions from feedyards. In a study by Erickson et al. (2000), dietary fiber in the form of corn bran was increased in cattle finishing diets. During the winter-spring study period, nitrogen volatilization rates were decreased, but animal performance was adversely affected. In another study by Bierman et al. (1999), beef cattle were fed different diets containing alfalfa hay, corn silage, and wet corn gluten feed (WCGF). The researchers concluded that dietary fiber and carbohydrate source affected the way feed cattle digested and excreted feed, resulting in changes to the amount of nitrogen excreted. Nitrogen excretion was highest for cattle fed a ration based on WCGF, but these cattle also had the highest performance. Farran et al. (2006) manipulated alfalfa hay and WCGF in beef cattle diets and made similar observations. Increasing alfalfa hay or WCGF intake resulted in an increase in nitrogen intake, nitrogen excretion, nitrogen volatilization, and cattle performance. They further concluded that recovery of nitrogen in the manure and finished compost was also increased, especially in the case of WCGF, as a result of increased organic matter content in the manure.

Cation-anion balance (DCAB)

Ammonia emissions are inhibited in low-pH environments, and lowering dietary cation-anion balance (DCAB) can potentially lower the pH of cattle urine. Notwithstanding other factors, lowering the pH of cattle urine may potentially reduce CAFO ammonia emissions. However, Erickson and Klopfenstein (2010) noted no effect of DCAB on nitrogen volatilization losses. Lowering urine pH may have little effect on ammonia emissions because the pen surface of feedyard pens may have significant buffering properties that strongly resist pH changes, tending to maintain a pH of approximately 8 or higher (Cole et al., 2009). Furthermore, cattle performance may be reduced by low-DCAB diets (Cole and Greene, 2004).

Post-excretion ammonia abatement methods

Post-excretion ammonia abatement strategies, such as improving manure management, can reduce the rate of nitrogen volatilization and ammonia emissions. Animal health considerations in post-excretion methods are not as great a concern when compared to nutritional methods; however, some manure management strategies, such as pen scraping, can be beneficial for animal health. Manure contains nitrogen and phosphorus, both of which contribute to the value of manure as a fertilizer. Nitrogen volatilization can reduce the nitrogen to phosphorus ratio (N:P) to below most plant requirements, thereby reducing the fertilizer value of the manure and requiring a greater land application area to avoid excessive phosphorus applications. Reducing ammonia emission rates from manure will enhance the fertilizer value of manure and lower ammonia emissions. Besides manure management, manipulating other factors such as the pH and moisture content of soil and/or manure can also affect ammonia emissions (Cole et al., 2008a).

Urease inhibitors, zeolites, fats, and other pen surface amendments

Based upon laboratory studies, a number of compounds can potentially be applied to feedlot pen surfaces to reduce ammonia emissions from feedyard surfaces (Varel, 1997; Varel et al., 1999; Shi et al., 2001; Parker et al., 2005; Cole et al., 2007). Substances such as zeolites (a microporous, aluminosilicate mineral), fats, and urease inhibitors such as N-(n-butyl) thiophsphoric triamide, cyclohexylphosphoric triamide, and phenyl phospohorodiamidate may change manure properties such as pH, ammonia adsorption potential, or hydrolysis potential, which, in turn, affects ammonia emission rates.

Urease inhibitors work by slowing down or blocking the hydrolysis of urea (found in urine) by the enzyme urease (found in feces). However, urease inhibitors must continually be applied to manure because they rapidly degrade (Powers, 2002; Parker et al., 2005). Applying some compounds, such as fats, may be accomplished indirectly through dietary supplementation. Zeolites and urease inhibitors have been shown to decrease ammonia emissions when applied

Studies on cattle fed high-concentrate, steam-flaked, corn-based diets have suggested that a moderate reduction of about 1.5 percent in dietary crude protein in the final 28 to 56 days of the feeding period may decrease ammonia emissions by as much as 25 percent with little adverse effect on animal performance. (Photo courtesy of S. Preece) as a surface amendment, but not when used as a dietary amendment (Varel 1997; Varel et al., 1999; Shi et al., 2001; Parker et al., 2005; Cole et al., 2007). Both dietary and surface amendments of fat appeared to decrease ammonia emissions (Cole et al., 2007). The dietary fat effect is likely because a proportion of fed fat is voided onto the feedyard surface after being excreted in undigested form by feedyard cattle. There were no significant effects on animal performance.

Lowering pH

One of the most important factors involved in ammonia emissions from surfaces is the pH of the emitting medium. In general, ammonia volatilization rates increase with pH. Lowering the pH of soil or manure can reduce ammonia emissions. With acidic conditions, given a constant temperature, more nitrogen will remain in the form of ammonium (NH_4^+), thereby decreasing the amount of ammonia available to volatilize. A significant reduction in ammonia emissions has been observed with acidifying amendments such as aluminum sulfate (alum), ferrous sulfate, phosphoric acid, or calcium salts.

Maintaining the low pH can be challenging, however, because manure may have a strong buffering capacity, which results in the pH eventually returning to a more basic level and a resumption of ammonia emission. Strong acids are more cost-effective than weak acids or acidifying salts, but they are more hazardous and not suitable for use in agricultural environments (Ndegwa et al., 2008).

Manure harvesting, storage, and application

Frequent pen cleaning may help capture nitrogen in the manure by decreasing loss to the atmosphere. Research in Nebraska (Erickson and Klopfenstein, 2010) revealed that cleaning pens once per month, as opposed to once after every 166-day feeding period, reduced apparent ammonia nitrogen losses by 24 percent. The effectiveness of the monthly cleaning strategy varied seasonally, being less in winter. This may be due to the accumulation of nitrogen that occurs in the pen surface manure pack during the winter, apparently the result of decreased ammonia losses during the colder months (Cole et al., 2009). In addition, the amount of nitrogen collected in the manure was 50 percent greater from pens cleaned monthly.

Covering manure to reduce its exposure to elements such as rain, sun, and wind is very effective at reducing ammonia emissions from storage areas. When manure is land-applied, immediate incorporation or injection into the soil has been shown to significantly reduce ammonia losses when compared to broadcasting alone (Ndegwa et al., 2008).

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The influence of diet crude protein level on odour and ammonia emissions from finishing pig houses

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Abstract

Feed trials were carried out to assess the influence of crude protein content in finishing pig diets on odour and ammonia emissions. Eight pigs (4 boars and 4 gilts), average initial weight 70.8 kg (s.e. 3.167) were housed in two pens that were isolated from the rest of a pig house at University College Dublin Research Farm, Newcastle, Dublin, Ireland. Four diets containing 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein were fed during six four-week feeding periods (one treatment per room). The first week of the feeding periods served to allow odour build up in the pens and as a dietary adjustment period. The pens had partially slatted floors that were cleaned and had all the manure removed after each four-week period. Odour and ammonia concentrations were measured on days 9, 14, 16, 21 and 23 of each trial period. Odour samples were collected in Nalophan bags and analysed for odour concentration using an ECOMA Yes/No olfactometer. The odour threshold concentration was calculated according to the response of the olfactometry panel members and was displayed in $\mathrm{Ou_E\,m^{-3}}$, which referred to the physiological response from the panel equivalent to that elicited by 40 $\mathrm{ppb\,v^{-1}}$ *n*-butanol evaporated in 1 $\mathrm{m^3}$ of neutral gas. Ammonia concentrations in the ventilation air were measured using Dräger tubes. The odour emission rates per animal for the 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein diets were 12.1, 13.2, 19.6 and 17.6 $\mathrm{Ou_E\,s^{-1}\,animal^{-1}}$, respectively ($P < 0.01$). The odour emission rate per livestock unit (500 kg) for the 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein diets were 77.6, 80.0, 115.8 and 102.9 $\mathrm{Ou_E\,s^{-1}\,LU^{-1}}$, respectively ($P < 0.01$). The ammonia emission rates per animal for the 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein diets were 3.11, 3.89, 5.89 and 8.27 $\mathrm{g\,d^{-1}\,animal^{-1}}$, respectively ($P \leqslant 0.001$). There was no significant difference in the average daily intake and the average daily gain for the four diets ($P > 0.05$). Manipulation of dietary crude protein levels would appear to offer a low cost alternative, in relation to end-of-pipe treatments, for the abatement of odour and ammonia emissions from finishing pig houses.

Keywords: Pig; Diet; Crude protein; Odour; Ammonia; Olfactometry; Abatement

1. Introduction

Pig production has changed in Ireland from a small scale enterprise carried out by a large number of farmers as an addition to the main farming enterprises, to a small number of specialist producers operating large scale units using high quality breeding stock and up to date techniques (Lara et al., 2002). Similar to other intensive farm operations, pig production generates substantial quantities of manure (faeces and urine) and mortalities, which lend themselves to a mixture of vapours, gases and dust combinations; odour and ammonia emissions are of particular environmental concern.

Odour emissions from pig production units can cause nuisance in the surrounding areas. Several guidelines and recommendations exist for protecting a neighbourhood from odour nuisance and are concerned on the one hand with the determination of set-back distances and, on the other hand, with the implementation of odour reducing techniques (Gallmann et al., 2001). The main sources of odour include building ventilation, manure storage and land spreading. Often these odorous mixtures are a consequence of animal manure decomposing anaerobically to form unstable intermediate by-products resulting in a complex mixture of over 168 volatile

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compounds of which 30 are odorous (O'Neill and Phillips, 1992). These compounds created from natural biological reactions include organic acids, aldehydes, alcohols, fixed gases, carbonyls, esters, amines, sulphides, mercaptans, aromatics and nitrogen hetrocycles.

The monitoring and reduction of ammonia emissions from livestock farming is a critical requirement of the European Commission Acidification Strategy and the EU Directive 2001/81/CE on National Emission Ceilings (Commission of the European Communities, 1997) which have called for a limitation of ammonia emissions from all EU countries. There are a number of on-farm sources of ammonia: animal housing, manure storage, field-applied manure and excreta deposited on the land by animals. Ammonia loss from the animal building is stimulated by the area of flooring covered by excreta, the chemical composition of the excreta, the temperature in the house and the ventilation rate of the house (Hutchings and Sommer, 2001). Of the total nitrogen ingested into the finishing animal approximately 50% is returned in the urine and 20% in the faeces (Jongbloed and Lenis, 1992). Ammonia is the product of the degradation of nitrogenous compounds. Bacteria in the faeces produce a urease enzyme, which converts the urea in the urine into ammonia. Atmospheric ammonia contributes to the acidification and eutrophication of soil and surface waters (Sutton et al., 1993; van der Eerden et al., 1998). Ammonia emissions in Europe originate mainly from agriculture, in particular from livestock farming. It is estimated that agricultural enterprises contribute 80–95% of ammonia emissions across Europe. Approximately 50% of ammonia emissions from pig production arises from pig buildings and the storage of manure (van der Peet-Schwering et al., 1999).

Manipulating the diet of finishing pigs by reducing the crude protein can reduce the total nitrogen excretion, reduce the ammonia emissions and alter the components of volatile fatty acids and other odorous compounds while not influencing the animal growth (Sutton et al., 1996). Phillips et al. (1999) identified dietary manipulation as the "best bet" for reducing ammonia emissions based on a ranking and weighting exercise. The aim of the present research was to study the influence of a range of crude protein levels on the generation of both odour and ammonia emissions from finishing pigs on partially slatted floors under controlled environmental conditions.

2. Methods

2.1. Animals

The finisher pigs used in this study were selected from a commercial herd, progeny of a Landrace X Large White Sow and a meat line sire. In total, 24 pigs, 12 boars and 12 gilts, were assigned one of four dietary treatments. Each dietary treatment was replicated 3 times with 8 pigs, 4 boars and 4 gilts, per treatment. Pigs were individually weighed at the start of the experimental period and each treatment was balanced for initial liveweight. Pigs were weighed after collection of the last odour and ammonia measurements and the average daily gain (ADG, $\mathrm{g\,d^{-1}}$) over the experimental period was calculated.

Two experimental pens were used at any one time and the diets were analysed in pairs. To minimise any seasonal effect, each dietary replicate was paired with a different diet.

2.2. Animal facilities

Two partially slatted floor pens in the pig finishing house on the University College Dublin Research Farm were individually sealed off from the rest of the building. Each pen was fitted with a variable speed centrifugal fan and thermostatically controlled electrical radiant heater. The pens had separate air inlets and outlets and could be heated and ventilated independently. The ventilation rate was calculated by measuring the airflow from the pens using a Testo 400™ handheld monitoring device fitted with a vane anemometer. The ventilation rate in both pens was kept constant during the trials at approximately 48.3 $\mathrm{m^3\,h^{-1}\,animal^{-1}}$ (s.e. 1.3). The internal temperature in the house was kept constant at approximately 21.0 °C (s.e. 0.32).

2.3. Feed and feeding

Pigs were provided with ad libitum access to un-pelleted meal through a single space hopper located on the solid floor of each pen. Feed intake was noted as the hopper was filled. Remaining feed at the end of the trial was recorded and the average daily feed intake (ADFI, $\mathrm{g\,d^{-1}}$) was calculated. Feed conversion ratio (FCR) was determined for each group. Water nipples were located over the slatted part of the pen.

Four diets (Table 1) were formulated using standard feeding values for the ingredients (O'Grady, 1996) to give diet crude protein contents of 220, 190, 160 and 130 $\mathrm{g\,kg^{-1}}$ fresh weight. Formulated levels of digestible energy (DE; 13.5 $\mathrm{MJ\,kg^{-1}}$) and 'ideal protein' (lysine 11 $\mathrm{g\,kg^{-1}}$) were maintained across all the diets.

The diets were fed during six four-week feeding periods. Week 1 allowed the pigs to acclimatise to the experimental diets and excreta levels to build up under the slatted area.

The pens were cleaned after each four-week period and all manure was removed from the underground storage tanks. The diets were mixed on site as required and each batch was sampled. Proximate analysis of diets for dry matter, ash and crude fibre was carried out ac-

Table 1
Composition and analysed chemical composition of experimental diets

Diets				
Crude protein (g kg^{-1})	220	190	160	130
Ingredient inclusion (kg ton^{-1})				
Wheat	637.5	722.5	810.0	887.7
Soya bean meal	309.2	224.2	136.7	60.0
Soya oil				13.3
DeviCare® Supplement[a]	25.0	25.0	25.0	25.0
Amino acid pack[b]	15.0	15.0	15.0	15.0
Analysed composition (g kg^{-1})				
Dry matter	873.2	875.1	873.0	877.1
Crude protein	209.0	184.6	157.4	131.7
Crude oil (ether extract)	29.4	26.9	27.3	33.0
Crude fibre	38.4	39.1	36.4	29.3
Ash	53.2	48.9	46.4	38.2
Gross energy (MJ kg^{-1})	15.98	15.82	15.52	15.81
Relative cost index[c]	1.00	1.05	1.15	1.30

[a] The supplement (DeviCare, Devenish Nutrition, Belfast, N. Ireland) provided minerals and vitamins (per kg diet) as follows 14,000 i.u. Vitamin A (4.2 mg retinol), 2800 i.u. Vitamin D (0.07 mg cholecalciferol), 80 i.u. Vitamin E (80 mg DL-alpha tocopherol), 120 mg copper as copper sulphate and 0.4 g selenium as sodium selenite.

[b] The amino acid pack contained supplementary synthetic lysine to maintain a dietary lysine content of 11 g kg^{-1}, and synthetic methionine, threonine and tryptophan on calcium carbonate carrier maintaining minimum dietary levels of 60%, 65% and 20% methionine + cysteine, threonine and tryptophan, respectively, and relative to lysine in the finished diet.

[c] The relative cost of each diet was estimated according to raw material prices at time of publishing and is largely influenced by the additional cost of synthetic amino acid use in low protein diets. The costs of both soybean meal and synthetic amino acids are influenced by market conditions, which will impact the accuracy of this index.

cording to the Association of Official Analytical Chemists (1984). Ether extract was determined according to the Soxhlet method, using a Soxtec System (Model 1043, Tecator, Sweden). Gross energy was determined in an adiabatic bomb calorimeter (Parr Instruments, Moline, IL, USA). The nitrogen content (crude protein × 6.25) of the diets was determined using a Leco Autoanalyser (Leco Corporation, St. Joseph, MI, USA).

2.4. Olfactometry

2.4.1. Collection of odour samples

Air samples were collected in 8 l Nalophan bags using a battery-powered vacuum pump and a rigid container. The samples were collected using the lung principle whereby the air was removed from the rigid container using a battery-powered vacuum pump at a rate of 2 l/min. A critical orifice controlled the air evacuation rate from the sampling container. This created a vacuum in the rigid container and caused the Nalophan bag to fill through stainless steel tubing with odorous air extracted from the exhaust vents. The air samples were sealed and stored in appropriate conditions. All the samples were analysed within 24 h. The odour measurements were carried out according to the European Standard prEN13725 (CEN, 2001) in the olfactometry laboratory in the Department of Agricultural and Food Engineering, University College Dublin. The odour and ammonia concentrations were measured on days 9, 14, 16, 21 and 23 of each four-week feeding regime. Ventilation rate and internal temperature measurements were carried out on the same days.

2.4.2. Measurement of odour threshold concentration

An ECOMA TO7 dynamic olfactometer (ECOMA, Honigsee, Germany) was used throughout the experimental period to measure the odour threshold concentration of the ventilated air from the fattening pens. The odour threshold concentration is defined as the dilution factor at which 50% of the panellist can just detect an odour. The panellists were previously selected by screening using the certified reference gas *n*-butanol (CAS 71-36-3) and only panellists that adhered to the code of behaviour for olfactometry were selected for odour measurements. The odour threshold concentration was calculated according to the response of the panel members and was displayed in $\mathrm{Ou_E\,m^{-3}}$, which referred to the physiological response from the panel equivalent to that elicited by 40 ppb v^{-1} *n*-butanol evaporated in 1 m^3 of neutral gas (CEN, 2001). Odour units were considered a dimensionless unit, but pseudo-dimensions of $\mathrm{Ou_E\,m^{-3}}$ have been commonly used for odour dispersion modelling in place of g m^{-3} (McGinley et al., 2000).

2.5. Measurement of ammonia concentration

Ammonia measurements were taken using Dräger tubes. The Dräger tubes have a measurement range of

0–30 ppm. The tubes were stored in the original packaging at room temperature in a shaded area until use. A hand operated bellows pump draws 100 ml of air through the tube with one stroke, during which the air contained in the pump chamber escapes through the exhaust valve. If ammonia is present, the reagent reacts resulting in a colour change of yellow to blue. The Dräger tubes provide a simple and easy way of measuring ammonia. They are designed for on-the-spot measurement and are expected to show a coefficient of variation of 10–15% (Dräger, 1998).

2.6. Statistical analysis

Data were analysed using the PROC MIXED function in SAS 6.14 for Windows (SAS 1996, SAS Institute Inc., Cary, NC, USA). Dietary influence on odour and ammonia was evaluated using a model that included diet as the fixed effect. The main influences of variation between sampling were removed by including internal room temperature and ventilation rate as random variables. Data were checked for outliers prior to analysis by the RSTUDENT option of SAS PROC GLM. No data points were identified as outliers and all observations were included for analysis ($n = 60$). Data is presented as the least-squared means of the three replicates with the standard error of the mean (s.e.).

3. Results and discussion

3.1. Dietary analysis and pig performance

Results of the dietary analysis are presented in Table 1. The analysed crude protein content of the diets was 209.0, 184.6, 157.4 and 131.7 $\mathrm{g\,kg^{-1}}$. The initial live weight of the pigs was 70.8 kg (s.d. 3.16 kg). The ADG was similar ($P > 0.05$) between the dietary treatments (721.5, 859.6, 800.7 and 768.8 $\mathrm{g\,d^{-1}}$, s.e. 0.09 in diets 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein, respectively). The ADI was similar ($P > 0.05$) between the dietary treatments (1.90, 2.15, 2.11 and 2.06 $\mathrm{g\,d^{-1}}$, s.e. 0.204 in diets 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein, respectively). Consequentially, FCR was similar ($P > 0.05$) between the diets (2.71, 2.49, 2.65 and 2.70, s.e. 0.147 in diets 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein, respectively).

3.2. Odour

The odour emission rates are reported per animal and per livestock unit (LU). One livestock unit is equivalent to 500 kg body weight. Table 2 shows that the odour emission rates were highest for the 190 $\mathrm{g\,kg^{-1}}$ crude protein diet. The odour emission rates ($\mathrm{Ou_E\,s^{-1}\,LU^{-1}}$) were significantly reduced by 33% and 31% for the 160 and 130 $\mathrm{g\,kg^{-1}}$ crude protein diets, respectively, in comparison to the 190 $\mathrm{g\,kg^{-1}}$ crude protein diet. Odour emission rate levels were similar ($P > 0.05$) between the 190 and 220 $\mathrm{g\,kg^{-1}}$ crude protein diets.

Peirson and Nicholson (1995) reported a reduction in odour emissions per kg liveweight from 0.540 to 0.317 $\mathrm{Ou_E\,s^{-1}\,kg^{-1}}$ (41% reduction) for a control and low nitrogen diet, respectively; the protein levels of the diets were not stated in the published data. Research reported by Hobbs et al. (1996) used gas chromatography–mass spectrometry to analyse the headspace gas for ten individual compounds commonly found in pig odour. Manure samples from two reduced crude protein diets, 131 $\mathrm{g\,kg^{-1}}$ crude protein and 139.3 $\mathrm{g\,kg^{-1}}$ crude protein and one commercial diet, 189.2 $\mathrm{g\,kg^{-1}}$ crude protein were analysed. Nine out of ten odorous compounds were significantly reduced using low crude protein diets ($P < 0.05$). The odour emission rates in this study, even from the low crude protein diets, were higher than some published emission rates from commercial pig units (Holste, 1998; Martinec et al., 1998). This might have been due to the orientation of the fans in relation to the manure surface in the experimental unit. High air velocity near the slurry surface caused by the location of the fans in the pens would increase the air movement above the manure surface, thus increasing the potential for the volatilisation of gases.

3.3. Ammonia

Table 3 indicates that ammonia emissions per animal per day were reduced by 62.4% when dietary crude protein was decreased from 220 to 130 $\mathrm{g\,kg^{-1}}$. This equates to a reduction of 8.1% for every 10 $\mathrm{g\,kg^{-1}}$ reduction in dietary crude protein.

Table 2
Mean odour emission rates

Crude protein	130 $\mathrm{g\,kg^{-1}}$	160 $\mathrm{g\,kg^{-1}}$	190 $\mathrm{g\,kg^{-1}}$	220 $\mathrm{g\,kg^{-1}}$	s.e. ($n = 60$)	P value
Odour						
$\mathrm{Ou_E\,s^{-1}\,animal^{-1}}$	12.11^{a}	13.24^{a}	19.57^{b}	17.59^{b}	1.5	0.005
$\mathrm{Ou_E\,s^{-1}\,LU^{-1}}$	77.64^{a}	80.03^{a}	115.80^{b}	102.88^{b}	8.1	0.009

^{a,b}Means with the same superscript within rows are not significantly different ($P > 0.05$).

Table 3
Mean ammonia emission rates and percentage reduction

Diets	$130\ g\,kg^{-1}$	$160\ g\,kg^{-1}$	$190\ g\,kg^{-1}$	$220\ g\,kg^{-1}$	s.e. ($n = 60$)	P value
Ammonia $g\,d^{-1}$ animal^{-1}	3.11^{a}	3.89^{b}	5.89^{bc}	8.27^{c}	0.509	0.001
Crude protein (analysed)	Total % reduction in NH_3 emissions		Total % reduction in NH_3 emissions for every $10\ g\,kg^{-1}$ reduction in CP (as analysed)			
209.0–184.6	28.78		12.0			
184.6–157.4	33.96		12.5			
157.4–131.7	0.05		7.8			
209.0–131.7	62.39		8.1			

[a,b,c]Means with the same superscript within rows are not significantly different ($P > 0.05$).

Similar results were obtained by Kay and Lee (1997) and Canh et al. (1998) between dietary levels of 187 and 130 $g\,kg^{-1}$ and between 16.5% and 12.5% crude protein, respectively. Reductions in ammonia emission equivalent to 9.8% per 10 $g\,kg^{-1}$ reduction in dietary crude protein are reported by Kay and Lee (1997). Comparing in vivo and in vitro measurements of ammonia release, Canh et al. (1998) report that emissions were reduced by 10% and 12.5%, respectively, per 10 $g\,kg^{-1}$ decrease in dietary crude protein. Kendall et al. (2000) reported a reduction in ammonia concentration from 29.6 to 12.9 ppm (approximately a 56% reduction) in the exhaust air from 12.6% and 9.35% crude protein diets, respectively, supplemented with synthetic lysine. The diets were fed to castrates and gilts over a six-week experimental period and ammonia measurements were measured with Dräger diffusion tubes over 4 h.

Peirson and Nicholson (1995) reported an approximate reduction of 33% in ammonia emissions per livestock unit between a control and a low nitrogen diet; the protein levels in the diets however were not stated.

Lower ammonia concentration in pig houses may also have useful benefits to the health of fattening pigs, resulting in associated improvements in pig performance and safety for stockmen. The Control of Substances Hazardous to Health (Health and Safety Executive, 1999) regulation specifies an eight hour time weighted average exposure of <25 ppm, 10 min exposure limit at 25–35 ppm and 0 min at >35 ppm. Animals in an integrated system are constantly exposed, so a maximum level of 20 ppm should be adhered to (Feddes and DeShazer, 1988). Smith et al. (1996) reported that weanling pigs, when given an option of fresh air or ammoniated air, showed a significant decrease in the amount of time spent in the area supplied with ammoniated air.

The use of Dräger tubes in this study gave an on-the-spot grab sample of the ammonia concentration in the air stream; a handheld electrochemical cell will be used for future experiments in order to measure the ammonia concentration and the concentration of other gases continuously.

3.4. Comparison of odour and ammonia emissions

In general as crude protein decreased, odour and ammonia emission rates decreased. However, odour emission rates were lower for the 220 than 190 $g\,kg^{-1}$ crude protein diets (Table 2). This might have been due to excess protein in the diet that could result in an imbalance in the feed C:N ratios or in insufficient carbohydrates to promote enhanced microbial decomposition resulting in reduced volatile fatty acids (VFA) (Sutton et al., 1996). Williams (1984) stated that pig odour offensiveness is largely related to the volatile fatty acids in the manure.

Ogink and Groot Koerkamp (2001) stated that reducing the emitting surface of the manure could reduce the emissions of odorous compounds. The implementation of dietary manipulation in combination with other abatement techniques such as reducing the emitting manure surface area, frequent manure removal and improved ventilation systems could lead to a significant reduction in odour and ammonia emission rates (EPA, 2002).

3.5. Cost

As seen in Table 1, the relative cost of each diet was estimated. It was largely influenced by the cost of the synthetic amino acids added to the diets low in crude protein. The estimated cost index of the 130, 160, 190 and 220 $g\,kg^{-1}$ crude protein diets was 1.30, 1.15, 1.05 and 1.0, respectively. Synthetic amino acids may be utilised to reduce the excretion of nitrogen in the manure and reduce the ammonia emissions but the cost of adding them to the diets must be taken into consideration relative to the cost of conventional protein sources. The formulation of a synthetic amino acid balance in the diets of finishing pigs as a replacement for protein is more expensive than conventional finishing diets. Fluctuations in the market price of soya bean meal and synthetic amino acids will affect the cost implications of this strategy. Low dietary crude protein levels would appear to offer a low cost alternative, in relation to end of pipe treatments, of reducing odour and ammonia emissions from finishing pig houses.

4. Conclusions

Dietary crude protein levels of 130, 160, 190 and 220 $\mathrm{g\,kg^{-1}}$ were fed to finishing pigs during six four-week feeding periods.

- The odour emission rates were highest for the 190 $\mathrm{g\,kg^{-1}}$ crude protein diet. A reduction in the odour emission rates of greater than 30% is achievable.
- The ammonia emission rates were highest for the 220 $\mathrm{g\,kg^{-1}}$ crude protein diet. The ammonia emissions per animal per day were reduced by 62.4% when dietary crude protein decreased from 220 to 130 $\mathrm{g\,kg^{-1}}$. This equates to a reduction of 8.1% for every 10 $\mathrm{g\,kg^{-1}}$ reduction in crude protein between 209.0 and 131.7 $\mathrm{g\,kg^{-1}}$ of total dietary content.
- Future work on ammonia and odour emission rates from pig and poultry units will utilise a handheld electrochemical cell in order to continuously monitor ammonia and other odorous gases.

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Exhibit 38

The impact of ammonia emissions from agriculture on biodiversity

Summary

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As levels of other air pollutants have declined, ammonia emissions in the UK have been rising since 2013, with significant implications for biodiversity and human health. The agricultural sector is the biggest contributor to ammonia pollution, producing 82 per cent of all UK ammonia emissions in 2016. The aim of this study is to provide an overview of the existing evidence in three main areas:

- The impacts of ammonia emissions from agriculture on biodiversity in the UK.
- The interventions available to reduce ammonia emissions from agriculture and their effectiveness.
- The costs of the interventions, and how these compare to the costs of inaction on ammonia emissions, both in terms of impacts on biodiversity and wider impacts (e.g. on human health).

Impact of ammonia on biodiversity

Ammonia itself and the nitrogen deposition resulting from ammonia emissions negatively affect biodiversity. Ammonia is one of the main sources of nitrogen pollution, alongside nitrogen oxides. A major effect of ammonia pollution on biodiversity is the impact of nitrogen accumulation on plant species diversity and composition within affected habitats. Common, fast-growing species adapted to high nutrient availability thrive in a nitrogen-rich environment and out-compete species which are more sensitive, smaller or rarer. Ammonia pollution also impacts species composition through soil acidification, direct toxic damage to leaves and by altering the susceptibility of plants to frost, drought and pathogens (including insect pests and invasive species). At its most serious, if changes in species composition and extinctions are large, it may be that remaining vegetation and other species no longer fit the criteria for that habitat type, and certain sensitive and iconic habitats may be lost.

Certain species and habitats are particularly susceptible to ammonia pollution. Bog and peatland habitats are made up of sensitive lichen and mosses which can be damaged by even low concentrations of ammonia. Grasslands, heathlands and forests are also vulnerable. However, much of the wider evidence on biodiversity impacts relates to all nitrogen pollution, rather than just ammonia.

There is far less evidence on the impact of ammonia, and nitrogen more generally, on animal species and the wider ecosystem. However, animal species depend on plants as a food source; therefore herbivorous animals are susceptible to the effects of ammonia pollution. There is a negative correlation between flower-visiting insects, such as bees and butterflies, and nitrogen pollution. Ammonia affects freshwater ecosystems through direct agricultural run-off leading to eutrophication (accumulation of nutrients, leading to algal growth and oxygen depletion) and also has toxic effects on aquatic animals that often have thin and permeable skin surfaces.

Quantifying the economic impact of ammonia emissions on biodiversity is challenging and the methods used are subject to debate. Available estimates suggest that loss of biodiversity due to ammonia emissions could have impacts in the UK which can be valued, conservatively, at between £0.20 and £4 per kg of ammonia. Combining this with the monetised health impacts, our conservative estimate of the total costs from both health and biodiversity impacts of ammonia in the UK is £2.50 per kg of ammonia (though the range of possible values is from £2 to £56 per kg). This conservative estimate, combined with projected emission data, suggests that if no action is taken to reduce ammonia emissions, the negative impacts on the UK in 2020 could be equivalent to costs of over £700m per year. However, there are significant uncertainties in these values.[1] The range of possible costs, based on the estimates in the literature and best available projections for emissions, are between £580m and £16.5bn per year.

Reducing ammonia emissions

Ammonia emissions can be reduced by managing the production, storage and spreading of manure. Some of the most established ways to do this are summarised in Table 1. Figure 1 provides an overview of the cost-effectiveness, acceptability and strength of evidence for a range of specific interventions. Based on our estimates above, the impacts of ammonia can be conservatively costed at £2.50 per kg, which is equivalent to £1 of damage being caused by every 0.4kg of ammonia emitted. On this basis, any intervention which exceeds this threshold – to the right of the line in Figure 1 – could

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[1] See report section 2.5 for the full data and caveats. The £700m figure comes with a range between £580 million and £16.5 billion (based on variation within the published literature and exact methodology used). £700m was calculated by combining an estimate of £2 per kg for health impacts (*based on the Watkiss (2008) and Dickens et al. (2013) estimates which are most relevant to the UK context, use the UK standard values for a value of life years lost (VOLY) and do not include additional costs e.g. related to crop damage*) with an estimate of £0.42 for impacts on biodiversity (*based on the most comprehensive and recent analysis in the UK context, by Jones et al. (2018)*) to arrive at a conservative estimate of the total costs from both health and biodiversity impacts of £2.50 per kg of NH_3. Combining this with projected emission data, we can produce an indicative estimate of overall cost equivalents to the UK of ammonia emissions. If no action is taken to reduce emissions, the costs are estimated to be over £700m per year.

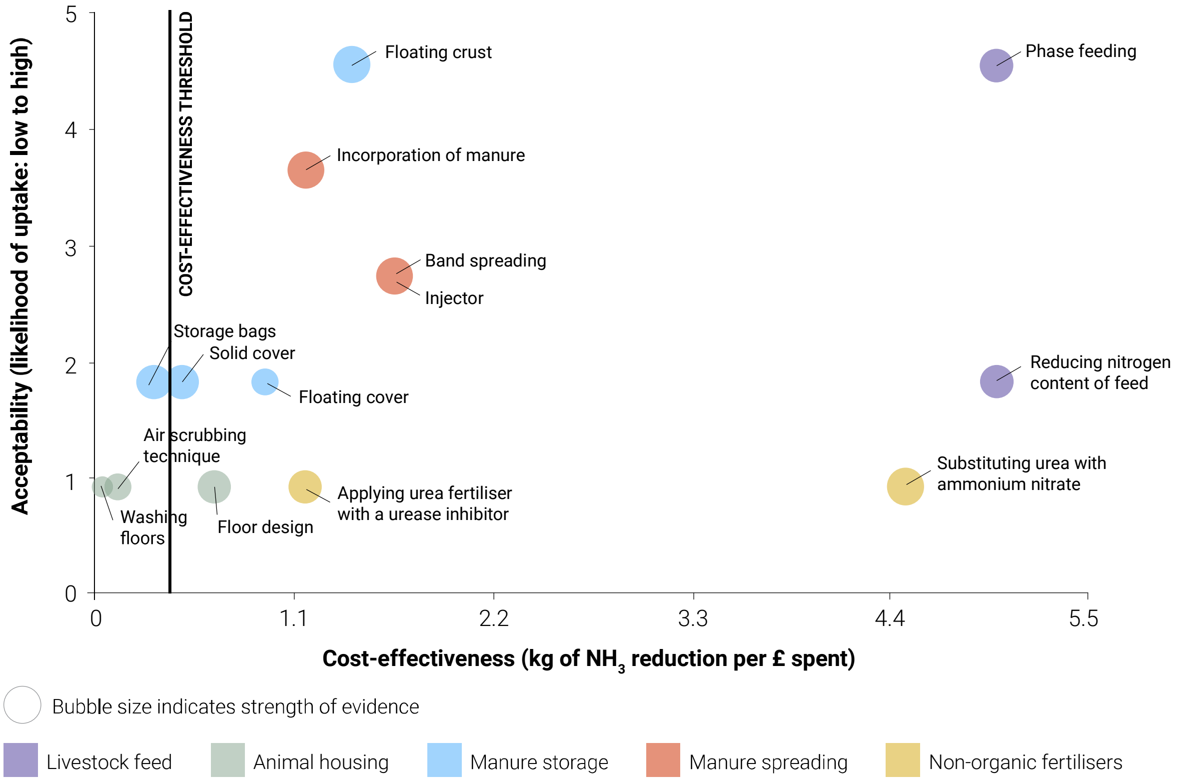
be considered cost-effective, which would include the majority of interventions. However, the whole ammonia lifecycle needs to be taken into account. If emissions are reduced immediately after manure production (e.g. through collection), but then not reduced in later stages (e.g. in storage or in spreading), then the emissions benefits at earlier stages are negated. Therefore, interventions need to be used in combination, spanning the whole lifecycle of manure production, storage and application. This also highlights the benefits of feed-based approaches which reduce the amount of ammonia produced in manure in the first place. It is also important to consider the interplay of ammonia emissions with those of other polluting gases, which might be negatively affected by some interventions, or by ammonia reductions generally. For example, excess nitrogen, whilst reducing species richness, can increase the volume of plant matter overall, which has benefits for carbon sequestration.

From a policy perspective, a mix of regulation, incentives and education are likely to be necessary to support the implementation of interventions. Evidence from the Netherlands and Denmark suggests that for interventions with a high level of acceptability to the agricultural sector, regulatory approaches can be introduced fairly quickly to support compliance. Where there are high upfront costs for farms, or a lower level of acceptability or knowledge, there may be more need for incentives and education, alongside voluntary actions in the first instance, before regulation can be effectively introduced. It may also be that different approaches are needed across different farm types or sizes. Wider education and awareness-raising may also be needed to help build understanding of the importance and costs of ammonia reduction amongst the public and in the retail sector, so that the full cost of these measures are not placed solely on the agricultural sector and/or government subsidies.

Table 1. Summary of categories of interventions to reduce ammonia emissions

Method	Description	Reduction in ammonia emissions	Limitations	Implementation cost (£/kg of ammonia)
Livestock feed	Reducing the amount of excess protein in livestock diets	10% to 60%	Higher feeding costs to farmers and potential for imbalanced nitrogen levels in the farm as the full use of grass production is not guaranteed	-2.3 to 2.3
Animal housing	Designing animal housing to better contain manure and reduce emissions	10% to 90%	High investment costs to refurbish or replace existing buildings	1 to 27
Manure storage	Storing manure for spreading as fertiliser in ways that reduce emissions	30% to 100%	Difficult to mix covered slurry; different covers are suitable for different quantities	0.4 to 3
Manure spreading	Methods for spreading manure as fertiliser that reduce emissions	0% to 99%	Effectiveness varies	-0.6 to 2.3
Non-organic fertilisers	Using manufactured fertilisers in ways that reduce emissions	40% to 90%	Ammonia emissions from organic fertilisers in the UK only account for a small proportion (c.10%) of ammonia emissions	-0.6 to 2.3

Figure 1. Bubble diagram showing strength of evidence, cost effectiveness and acceptability for a range of interventions to reduce ammonia emissions



Source: RAND Europe analysis. Cost-effectiveness and strength of evidence from Bittman et al. (2014). Acceptability based on likelihood of uptake from low (1) to high (5) as set out in Newell Price et al. (2011).

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Exhibit 39

An Inventory of Mitigation Methods and Guide to their Effects on Diffuse Water Pollution, Greenhouse Gas Emissions and Ammonia Emissions from Agriculture

Newell Price, J.P., Harris, D., Taylor, M., Williams, J.R., Anthony, S.G.,
Duethmann, D., Gooday, R.D., Lord, E.I. and Chambers, B.J. (ADAS),
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December 2011

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INTRODUCTION

Background

The UK Government is committed to obligations under the EU Water Framework Directive (including the Nitrates Directive, the Freshwater Fish Directive, the Bathing Waters and the Shellfisheries Directives), the UNECE Convention on Long-Range Transboundary Air Pollution (the Gothenburg Protocol), the EU National Emission Ceilings Directive (NECD), the Kyoto Protocol and Climate Change agreements amongst EU countries. As a result of the above Directives and International agreements, the UK is required to:

- achieve good ecological and chemical status of surface and ground waters by 2015 (provided that the cost of doing so is not disproportionately expensive or technically unfeasible);
- reduce ammonia emissions with agreed ceiling targets established for 2010 and ongoing negotiations for revised ceilings to be met by 2020;
- reduce emissions of the principal greenhouse gases (nitrous oxide, methane and carbon dioxide-CO_2) by 12.5% below the 1990 level over the first commitment period, 2008-2012.

Furthermore, the UK also has a domestic target to reduce greenhouse gas emissions (including international aviation and shipping emissions) by 80% (below the 1990 level) by 2050. The UK, therefore, has a number of challenging goals that need to be considered in an integrated way, in order to identify where certain actions may have conflicting unintended consequences (i.e. ‘pollution swapping’ situations) and to determine best options (i.e. to identify ’win-win’ situations).

Aim

The purpose of this document is to provide summarised information on a range of mitigation methods (options) to reduce diffuse water pollution, air pollution and greenhouse gas (GHGs) emissions. The aim is to help users in developing policies and selecting suitable mitigation methods to meet the inter-acting and occasionally conflicting obligations listed above.

The document lists mitigation methods (options) and assesses the impact of each method on nitrogen losses (nitrate, nitrite, ammonium), phosphorus (total and soluble), sediment, biological oxygen demand (BOD) and faecal indicator organism (FIO) losses to water, and gaseous emissions (i.e. ammonia, nitrous oxide, methane and carbon dioxide) to air. Where possible, the effect of a mitigation method on emissions to water and air has been quantified for the field area to which the method is applied or on a farm scale basis etc. Where such data are not available, the direction of change in emissions has been indicated.

This document builds upon information contained in the previous “DWPA (Diffuse Water Pollution from Agriculture) User Manual”; the “Ammonia Mitigation User Manual”; and “A Review of Research to Identify Best Practice for Reducing Greenhouse Gases from Agriculture and Land Management”, viz:

DWPA User Manual (part of Defra project ES0203) compiled data from previous Defra studies (e.g. projects NT2511, PE0203, and ES0121) to summarise information on the effect of 44 potential upon methods to control diffuse water pollution from agriculture.

Ammonia Mitigation User Manual (Defra project AQ0602) compiled evidence from a large body of Defra-funded research on the effect of 25 potential mitigation methods to reduce ammonia emissions from agriculture.

Review of Research to Identify Best Practice for Reducing Greenhouse Gases from Agriculture and Land Management (part of Defra project AC0206) compiled evidence from Defra-funded projects (e.g. projects CC0229, CC0262, CC0272, and ES0127) and published scientific studies to assess the effect of 8 main mitigations methods for reducing GHG emissions from agriculture. A further 7 'future potential mitigation methods' and 6 'speculative mitigation methods' were also identified.

Farm typologies

Detailed farm typologies and practices were established from which baseline pollutant losses could be calculated. The farm typologies were based on the 'Robust Farm Types' (RFT) used in the Defra Farm Business Survey (defined by the dominant source of revenue) and the Defra June Agricultural Census for 2004 (Defra, 2004a), Table 1.

Table 1. "User Guide" farm typologies and mapping to the Defra 'Robust Farm Types'.

"User Guide" Farm Typology	**'Robust Farm Type'**
Dairy	Specialist Dairy
Less Favoured Area (LFA) - Grazing Livestock	Less Favoured Area (LFA) - Grazing Livestock
Lowland - Grazing Livestock	Lowland - Grazing Livestock
Mixed	Mixed
Combinable Crops	Specialist Cereal
Roots/Combinable Crops	General
Indoor Pigs	Specialist Pig
Outdoor Pigs	Specialist Pig
Poultry	Specialist Poultry
Horticulture	Horticulture

Note: 'Other' RFTs excluded as they were of limited economic (and agricultural) importance.

Total crop areas and livestock numbers for each farm typology were derived from the proportions of the land area occupied by each crop type and the stocking densities of each livestock type in the Defra June Agricultural Census for 2004 (Defra, 2004a). Farm practice information was derived from a number of sources, including the British Survey of Fertiliser Practice for 2004 for fertiliser types, application rates and timings; (Goodlass and Welch, 2005) and Smith *et al*. (2000; 2001a; 2001b) for the timing and rate of livestock manure applications to land. A detailed description of the farm typologies is provided in Appendix I, with summary information provided in Table 2 below.

Note: All pig manure production was allocated for the combinable crops farm and all poultry manure production (after accounting for amounts incinerated) to the roots/combinable crops farm to facilitate nutrient flow auditing.

Table 2. Summary of twelve farm typologies.

Farm System	Number of livestock on farm				
	Cattle > 1 year	**Calves < 1 year**	**Sheep & Lambs**	**Pigs**	**Poultry**
Combinable crops	0	0	0	0	0
Combinable + pig manure	0	0	0	0	0
Roots/combinable crops	0	0	0	0	0
Roots/combinable + poultry manure	0	0	0	0	0
Dairy	170	45	104	0	0
Grazing-Lowland	82	39	354	0	0
Grazing-LFA	52	20	697	0	0
Mixed	116	40	393	400	2,605
Indoor pigs	0	0	0	3,524	0
Outdoor pigs	0	0	0	440	0
Poultry	0	0	0	0	81,357
Horticulture	0	0	0	0	0

Farm System	Excreta managed as manure (%)	Field area (ha)	Mean fertiliser application rate[+]	
			kg N/ha	**kg P_2O_5/ha**
Combinable crops	0	172	182	42
Combinable + pig manure	100	172	171	36
Roots/combinable crops	0	180	137	44
Roots/combinable + poultry manure	100	180	135	42
Dairy	62[*]	114	115	20
Grazing-Lowland	36[*]	101	56	17
Grazing-LFA	24[*]	146	23	7
Mixed	39[*]	155	92	29
Indoor pigs	100	0	0	0
Outdoor pigs	0	18	0	0
Poultry	80[**]	0	0	0
Horticulture	0	18	86	39

[*] *remainder deposited by grazing livestock in the fields*
[**] *remainder is sent for energy generation*
[+] *mean overall of farm area*

METHODS

In compiling the 83 methods summarised in this "User Guide", a wide range of sources of information were considered (in addition to the projects mentioned above), viz:

- Cost Action 869: Mitigation Options for Nutrient Reduction in Surface Water and Ground Waters
- Scottish Government: Land Management Contracts
- Scottish Environment Protection Agency (SEPA): Best Management Practices
- United States Environment Protection Agency (USEPA): Best Management Practices
- Methods promoted as part of the England Catchment Sensitive Farming Delivery Initiative (ECSFDI)

The project has provided 'broad' estimates of the cost and effectiveness of the various mitigation methods. On each method sheet:

- *costs are expressed per unit of land, at the farm scale or per m^3/tonne of manure etc. (as appropriate for each mitigation method)*
- *effectiveness is expressed for the target area on which the method was applied* or at a farm scale (as appropriate for each mitigation method).

Effectiveness bands, or direction of change, at the farm-scale have also been summarised in spreadsheet format (referred to as the 'farm-scale spreadsheets') for each farm typology and for both 'permeable' and 'impermeable' soils for the 700-900 mm climate band (Six climate bands were used in total for this project; <600mm, 600-700mm, 700-900mm, 900-1200mm, 1200-1500mm and >1500mm). These effectiveness bands provided the basis of modelling work to quantify the effectiveness of groups of methods at the farm and national scale. In another part of this project, the effectiveness values were expanded to account for different impacts by pollutants pathway and source (e.g. slurry, FYM etc.). The main output of this related work was the "FARMSCOPER" tool (FARM SCale Optimisation of Pollutant Emissions Reduction), which estimates baseline pollutant losses and can assess the impacts of individual and multiple methods for a range of farm types.

The mitigations methods were grouped into the following seven categories:

- *Land use change*
- *Soil management*
- *Crop & livestock breeding*
- *Fertiliser management*
- *Livestock management*
- *Manure management*
- *Infrastructure*

The mitigation methods are not presented in any order of effectiveness. Each method is given a number and a brief title for reference. This is followed by a description of the method and its application, arranged into ten sections:

- *Pollutants targeted* (including the direction and approximate magnitude of change where it is possible to provide a range)
- *Farm typologies applicable*

- *Description and Rationale*
- *Mechanism for action*
- *Potential for applying the method*
- *Practicability*
- *Likely uptake*
- *Costs*
- *Effectiveness*
- *Other benefits* (including risk of 'pollution swapping')

(i) Pollutants targeted: A table showing the impact of the method in terms of direction and approximate magnitude of change or no impact (~) is provided; based on a combination of available data from the scientific literature and the expert judgement of the project team. Table 3 shows the 'arrow strengths' used in the effectiveness tables and how they link to effectiveness classes.

Table 3. Method effectiveness classes, ranges and arrow strengths

Description	Average	Range	Description	Arrow strength
None	**0**	**0**	None	~
Low	**10**	**1 to 30**	Low	↓
Moderate	**40**	**20 to 80**	Moderate	↓↓
High	**70**	**50 to 90**	Very High	↓↓↓

Note: Arrow directions may also be upwards where a method increases the loss of a pollutant.

(ii) Farm typologies applicable: A table showing the farm typologies to which the method is applicable.

(iii) Description and rationale: A description of the actions to be taken to implement the method; and the broad reason for adopting the method as a means of reducing pollutant loss.

(iv) Mechanism of action: A more detailed description of the processes involved and how the method achieves a reduction in pollutant loss.

(v) Potential for applying the method: An assessment of the farming systems, regions, soils and crops to which the method is most applicable.

(vi) Practicability: An assessment of how easy the method is to adopt, how it may impact on other farming practices and possible resistance to uptake.

(vii) Likely uptake: The likely level of uptake (in the next ten years) given the current economic climate and levels of regulation and enforcement.

(viii) Costs: 'Broad' estimates are presented of how much it would cost to implement each method, taking into account annual running costs and annual charges for any capital investment required (derived by amortising the required investment over the anticipated write-off period at an interest rate of 7%).

Where relevant, costs are presented on a per hectare (ha) basis and/or at a farm scale (as appropriate for each mitigation method). For livestock and manure management methods, costs are also presented per cubic metre of slurry/solid manure or per head of livestock (see Appendix II).

Farm level costs relate to the specific farm typologies summarised in Table 2 (and described more fully in Appendix I). The assumptions used in calculating the costs of each method are summarised in Appendix II. Costs may be one-off costs, annual cash costs, annualised capital costs (amortised) or annual and amortised costs, as appropriate for each mitigation method. The types of cost are indicated for each method. Some of the methods may lead to the land not being farmed, unless compensation is paid or a scheme for land management is provided. Also, reductions in stocking rates or the area of land farmed will have a consequent impact on the agricultural supply industry, which has not been taken into account in the cost estimates.

Note: Method costs are *sensitive* to the detail and scale of an individual farm enterprise. Also, the net costs of many mitigation methods are *very sensitive* to short-term changes in the cost of inputs, notably fuel and fertiliser, and the market value of produce. Caution is advised in applying the cost estimates to individual enterprises or scaling up to the national level.

(ix) Effectiveness: Effectiveness classes, or direction of change, are provided for the main pollutants affected by each mitigation method. The effectiveness of a method on a specific pollutant was assigned to an effectiveness range, based on currently available research data or where data did not exist the expert judgement (based on the assumed mechanism of action) of the project team; Table 3.

All estimates of effectiveness have a *high level of uncertainty* associated with them, and where a range of effectiveness is given, it is still possible for effectiveness values to fall outside this range in individual circumstances. The effectiveness range provides a band in which the majority of values are likely to fall.

Effectiveness (where possible) is expressed as a percentage reduction relative to the baseline pollutant loss. The effectiveness classes reflect natural variation in their efficiency and variation according to the magnitude of the baseline loss, as well as uncertainty.

Baseline losses

For each of the farm typologies, pollutant baseline losses were estimated for ‘permeable’ (i.e. freely drained) and ‘impermeable’ (i.e. poorly drained) soils, and for six climate zones based on annual average rainfall values between 1961 and 1990 (< 600mm; 600-700mm; 700-900mm; 900-1200mm; 1200-1500mm; and >1500mm).

Baseline losses were also divided into specific sources (components originating from the soil, from manure/excreta and from fertiliser), areas and loss pathways using environmental models (Anthony, 2006; Anthony *et al*., 2008a), supported by field data and expert judgement. This approach enabled effectiveness classes to be assigned to specific sources and pathways of pollutant loss. The ‘overall’ effectiveness of a method depends on the relative importance of the baseline losses identified. For example, some methods such as ‘adopt reduced cultivation systems’ or ‘manage over winter tramlines’ can have a significant impact on losses of sediment and particulate P, via the surface runoff pathway (Deasy *et al*., 2008). However, on drained soils the overall effectiveness of these methods depends on the relative contribution of the surface compared with sub-surface (i.e. drainflow) pathway to overall pollutant losses. It can be difficult to predict the overall effectiveness of a method without detailed information on the relative contribution of different delivery pathways to total baseline losses. *It is often the case that our predictions are limited by a lack of field data and in* *these instances we are reliant on environmental models (and expert judgement) for guidance*.

The following models were used to support baseline loss calculations for the farm typologies, viz:

Nitrate

Nitrate losses were estimated using a combination of the NEAP-N, NITCAT, N-CYCLE, EDEN and MANNER models (Lord and Anthony, 2000; Lord, 1992; Gooday *et al*., 2007; Chambers *et al*., 1999).

Phosphorus and sediment

Phosphorus and sediment loads were estimated using the PSYCHIC model (Version 8.1; Davison *et al*., 2008; Stromqvist *et al*., 2008; Collins *et al*., 2007). PSYCHIC is a process based, monthly time-step model, with explicit representation of surface and drainflow hydrological pathways, particulate and solute mobilisation, and incidental losses associated with fertiliser and manure applications. Outputs from PSYCHIC have been used to support phosphorus and sediment gap analyses for rivers and lakes in England (e.g. Anthony *et al*., 2008b), and its use here provides consistency across a number of projects used to support government policy development.

Ammonia

Ammonia (NH_3-N) emissions from fertiliser applications were estimated using the NT26-*AE* model (Chadwick *et al*., 2005) and fertiliser use for each farm typology was derived from the British Survey of Fertiliser Practice for 2004 (Goodlass and Welch 2005). Ammonia emissions from all other sources were estimated using NARSES (Webb and Misselbrook, 2004).

Nitrous oxide

Direct nitrous oxide (N_2O-N) emissions and *indirect* N_2O emissions (as a result of ammonia volatilisation and nitrate leaching losses from fertiliser, excreta and managed manures) were estimated using the IPCC tier 1 methodology (IPCC, 2006; Baggott *et al*., 2006).

Methane

Methane (CH_4) emissions were estimated using the IPCC (2006) tier 1 methodology (IPCC, 2006), using default coefficients derived for Western Europe and national data on manure management. For dairy cows, tier 2 calculations were used that took into account animal productivity (litres of milk produced), live weight and fat content of the milk.

Table 4 summarises the range of baseline losses from each of the farm typologies.

Effectiveness and method implementation

The effectiveness classes (bands) assigned to each method was specific to the way the method was implemented and to the farm typologies described. Where a method cannot be applied to a particular farm type it has been shown as non-applicable (×) in the ‘applicability’ tables.

Scales of effectiveness

The effectiveness tables in each method sheet summarise the magnitude of effect on each pollutant for the target area on which the method was applied or at a farm scale (as appropriate for each mitigation method).

Effectiveness classes are provided for nitrate, nitrite and ammonium, phosphorus (total and soluble), sediment, BOD and FIOs, ammonia, nitrous oxide and methane. We have assumed that the behaviour of nitrite (NO_2) is closely associated with that of ammonium and nitrate (the two dominant processes involved with NO_2-N turnover are the nitrification of NH_4-N and the reduction of NO_3-N during denitrification). Moreover, Defra project ES0121 (‘COST-DP: Cost effective diffuse pollution mitigation’) concluded that mitigation of nitrite loss was best dealt with through the mitigation of its precursors, particularly NH_4-N. For carbon dioxide (CO_2), we have taken into account *on-farm energy use*; energy use beyond the farm-gate, such as the manufacture of fertilisers or transport of food products, has not been taken into account, which would be the case for a full life-cycle analysis.

Table 4. Total baseline loss ranges for farm typologies

Farm System	***Main waterborne pollutants (kg/ha)***		
	Nitrate (N)	***Total phosphorus (P)***	***Sediment***
Combinable crops	20 - 40	0.02 - 0.8	10 - 800
Combinable + pig manure	65 - 115	0.2 - 1.0	10 - 800
Roots/combinable crops	25 - 45	0.02 - 0.9	10 - 850
Roots/combinable + poultry manure	40 - 90	0.2 - 1.0	10 - 850
Dairy	15 - 50	0.2 - 0.8	5 - 300
Grazing - Lowland	7 - 25	0.1 - 0.5	5 - 250
Grazing - LFA	5 - 15	0.05 - 0.3	5 - 150
Mixed	20 - 50	0.2 - 0.8	10 - 450
Indoor pigs	no land	no land	No land
*Outdoor pigs**	100 - 150	1 - 3	400 - 1200
Poultry	no land	no land	no land
Horticulture	20 - 35	0.01 - 0.7	10 - 650
Farm System	**Main airborne pollutants *(kg/farm)***		
	Ammonia $(N)^{x}$	***Nitrous oxide*** $(N)^{xx}$	***Methane*** (CH_4)
Combinable crops	1,160	860	0
Combinable + pig manure	5,900	1,300	0
Roots/combinable crops	860	660	0
Roots/combinable + poultry manure	5,540	950	0
Dairy	4,300	720	21,200
Grazing - Lowland	1,150	380	7,130
Grazing - LFA	720	330	6,720
Mixed	5,700	930	12,840
Indoor pigs	15,700	390	18,120
Outdoor pigs	180	230	900
Poultry	16,100	240	4,850
Horticulture	60	80	0

* Mean over 2 years

[x] Multiply by 17/14 to convert to ammonia (NH_3) losses

[xx] Multiply by 44/28 to convert to nitrous oxide (N_2O) losses

(x) Other pollutants: This section provides an assessment of how the emission of other pollutants (not included in the main ‘effectiveness section’) might either be reduced or increased if the method was to be adopted.

The ‘broad’ cost and effectiveness values for each method relate specifically to the farm typologies used in this project (Table 2). They cannot simply be applied to individual farm enterprises or scaled-up to a national level, without a detailed sensitivity analysis.

Method 1A – Convert arable land to unfertilised and ungrazed grass

Direction of change for target pollutants on the area converted to unfertilised grass.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓↓	↓↓↓	↓↓↓	↓↓	↓	↓↓	~	~	↓↓↓	↓↓↓	~	↓*

* Plus enhanced soil carbon storage.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	✓	✓	×	×	×	✓

Description: Change the land use from arable cropping to unfertilised grassland (without livestock) and associated manure inputs.

Rationale: There are only small losses of nitrate (NO_3) in drainage waters from arable reversion grasslands and the permanent vegetation cover minimises the erosion of soil particles and loss of associated particulate phosphorus (P) in surface runoff.

Mechanism for action: N uptake by the permanent vegetative cover and N immobilisation into accumulating soil organic matter provide a long-term sink for N. Conversion to permanent grassland also avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter and thereby increase the amount of NO_3 that is potentially available for leaching. In most cases, losses of NO_3 in drainage waters will respond rapidly to the change of land use.

At elevated soil P levels, significant reductions in the leaching of soluble P are unlikely to be achieved in the short-term (<10 years) because there are effectively no nutrient offtakes in grazed grass/livestock products The more immediate effect of this method would be to reduce particulate P losses in surface runoff, provided that the grassland was not compacted by vehicle traffic.

Potential for applying the method: The method is applicable to all arable land, but is potentially most suited to marginal and high erosion risk arable land.

Practicability: This is an extreme change in land use that is unlikely to be adopted by farmers without the provision of suitable incentives. It is likely to be particularly suited to areas where the converted land would have amenity or conservation value.

Likely uptake: Low, due to the high economic impact on a farm business.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on a reduction in cropped area (assumed to be 10% of all arable land) and loss of gross margin (as fixed costs stay the same).
Annual	200	200	2,200	7,500	35,000	9,500	

Effectiveness:

N: Conversion to ungrazed grassland would reduce NO_3 losses by around 90%; annual losses on converted land would typically be <5 kg N/ha. Ammonium and nitrite losses to water would also be reduced. Similarly, direct and indirect N_2O and NH_3 emissions would be reduced by around 90%.

P and sediment: Particulate P and associated sediment losses in surface runoff would be reduced by around 50%. Soluble P losses would be reduced in the longer-term.

Other pollutants: There would be reductions in energy use and increased carbon storage in the grassland soils; initially in the range 1.9 to 7.0 tCO_2e/ha/year. However, it is unlikely that these increases would be sustained over the longer-term (>50 years), as a new soil carbon equilibrium level would be reached.

Key references:

Chambers, B.J., Garwood, T.W.D. and Unwin, R.J. (2000). Controlling soil water erosion and phosphorus losses from arable land in England and Wales. *Journal of Environmental Quality*, 29, 145-150.

Chalmers A.G., Bacon E.T.G. and Clarke J.H. (2001). Changes in soil mineral nitrogen during and after 3-year and 5-year set-aside and nitrate leaching losses after ploughing out the 5-year plant covers in the UK. *Plant and Soil,* 228, 157-177.

Cuttle, S.P., MacLeod, C.J.A., Chadwick, D.R., Scholefield, D., Haygarth, P.M., Newell Price, J.P., Harris, D., Shepherd, M.A., Chambers, B.J. and Humphrey, R. (2007). *An Inventory of Methods to*

Control Diffuse Water Pollution from Agriculture (DWPA): User Manual. Final report for Defra project ES0203.

Dawson, J.J.C. and Smith, P. (2006). *Review of Carbon Loss from Soil and its Fate in the Environment*. Final report for Defra project SP08010.

Moorby, J.M., Chadwick, D.R., Scholefield, D., Chambers, B.J. and Williams, J.R. (2007). *A Review of Research to Identify Best Practice for Reducing Greenhouse Gases from Agriculture* and Land Management. Final report for Defra project AC0206.

Silgram, M. (2005). *Effectiveness of the Nitrate Sensitive Areas scheme 1994-2003.* Final report for Defra project M272/56. 22 pp.

Defra project NT0801 - To study nitrogen losses and transformations in arable land and to model these processes.

Defra project NT1312 - N measurements on set-aside.

Defra project NT1318 - Effect of cultivation on soil nitrogen mineralisation.

Defra project NT1504 - N mineralisation in arable conditions.

Defra project NT1510/11/12 - The measurement of mineralisation in field soils.

Defra project ES0106 - Developing integrated land use and manure management strategies to control diffuse nutrient losses from drained clay soils: BRIMSTONE-*NPS*.

Method 1B – Arable reversion to low fertiliser input extensive grazing

Direction of change for target pollutants on the area converted to extensive grazing.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓↓	↓↓	↓↓	↓↓	↓	↓↓	↑↑	↑↑	↑↑	↓↓	↑↑	↓*

*Plus enhanced soil carbon storage.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✗	✗	✓

Description: Change the land use from arable cropping to permanent grassland, with a low stocking rate and low fertiliser inputs.

Rationale: There are only small losses of NO_3 in drainage waters from arable reversion grasslands and the permanent vegetation cover minimises the erosion of soil particles and loss of associated particulate P in surface runoff.

Mechanism for action: N uptake by the permanent vegetative cover and N immobilisation into accumulating soil organic matter provide a long-term sink for N. Conversion to permanent grassland also avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter and thereby increase the amount of NO_3 that is potentially available for leaching. In most cases, losses of NO_3 in drainage waters will respond rapidly to the change of land use.

At elevated soil P levels, significant reductions in the leaching of soluble P are unlikely to be achieved in the short term (<10 years) because there are only low nutrient offtakes in cut grass/livestock products from extensively grazed systems. The more immediate effect of this method would be to reduce particulate P losses in surface runoff, provided that the grassland was not poached or badly compacted by vehicle traffic.

Potential for applying the method: The method is applicable to all arable land, but is potentially most suited to marginal and high erosion risk arable land.

Practicability: This is an extreme change in land use that is unlikely to be adopted by farmers without the provision of suitable incentives.

Likely uptake: Low, due to high economic impact on the farm business; it would require a significant change in farm business outlook and stockmanship skills.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on arable reversion to lowland grazing; some costs are amortised.
Annual	2,000	1,000	10,550	31,00	50,000	30,000	

Effectiveness:

N: Conversion to extensively grazed grassland would reduce NO_3 losses by around 80-90%; annual losses would typically be <10 kg N/ha. Ammonium and nitrite losses to water would also be reduced. Similarly, direct and indirect N_2O emissions would be reduced (as lower amounts of manufactured fertiliser N would be applied). However, NH_3 emissions from directly deposited excreta in the field and handled manures (during housing, storage and following land spreading) would be increased.

P and sediment: Particulate P and associated sediment losses in surface runoff would be reduced by around 50%. Soluble P losses would be reduced in the longer-term (provided that the grass was not poached).

FIOs and BOD: Losses would be increased due to the presence of livestock.

Other pollutants: There would be a reduction in energy use and increased carbon storage in the grassland soils; initially in the range 1.9 to 7.0 tCO_2e/ha/year. However, it is unlikely that these increases would be sustained over the longer-term (>50 years) as a new soil carbon equilibrium level would be reached. CH_4 and odour emissions would increase through the presence of livestock.

Key references:

Defra project NT0605 - To quantify nitrate leaching from swards continuously grazed by cattle.

Defra project NT1825 - Nitrate leaching in sustainable livestock. LINK project (LK0613).

Defra project ES0106 - Developing integrated land use and manure management strategies to control diffuse nutrient losses from drained clay soils: BRIMSTONE-*NPS*.

Method 2 – Convert arable/grassland to permanent woodlands

Direction of change for target pollutants on the area converted to woodland.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓↓	↓↓↓	↓↓↓	↓↓	↓	↓↓	↓*	↓*	↓↓	↓↓↓	↓*	↓**

* Only for farmland that previously had livestock.
** Plus enhanced soil carbon storage and woodland carbon sequestration.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Change the land use from agricultural land to permanent woodland.
Rationale: There are only small losses of NO_3 in drainage waters from permanent woodlands and the permanent cover, provided by leaf litter mulch and vegetation, minimises the erosion of soil particles and loss of associated particulate P in surface runoff.
Mechanism for action: Conversion to permanent woodland avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter and thereby increase the amount of NO_3 that is potentially available for leaching. Changing from arable and (to a lesser extent) grassland agriculture to permanent woodland will reduce soil N and carbon losses.
At elevated soil P levels, significant reductions in the leaching of soluble P are unlikely to be achieved in the short term (<10 years) because there are only low level of nutrient uptake by woodland over this time scale. The more immediate effect of this method would to reduce particulate P losses in surface runoff, provided that the woodland developed vegetation that covered the soil surface.
Potential for applying the method: The method is applicable to all farm types with land, but is potentially most suited to marginal arable land with a high erosion risk and/or close to surface waters.
Practicability: *This is an extreme change in land use* that is unlikely to be adopted by farmers without the provision of suitable financial incentives. It is likely to be particularly suited to areas where the converted land would have amenity or conservation value. *Note*: Grants are available to establish new woodlands (e.g. the Forestry Commission's English Woodland Grant Scheme).
Likely uptake: Low, due to dramatic change in land use and *short-term negative cashflow* in the farming business.
Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on establishment to harvest management, including timber sales @ 75 years (method applied to 2% of farm area).
Annual	-350	-350	-300	-450	-500	-50	-50	

Effectiveness:
N: Conversion to woodland would reduce NO_3 losses by around 90%; annual losses on converted woodland would typically be <5 kg N/ha. Similarly, direct and indirect N_2O emissions and NH_3 emissions would be reduced by around 90% (as no fertiliser N would be applied).
P and sediment: Particulate P and associated sediment losses in surface runoff would be expected to be reduced by around 50%; provided that best management practices as outlined in Forestry Commission (2003) were adopted.
FIOs and BOD: Losses would be reduced by a small amount (where livestock were previously present).
Other Pollutants: Converting arable land to permanent woodland would increase soil carbon storage by 1.9 to 7.0 tCO_2e/ha/year. However, it is unlikely that these increases would be sustained over the longer-term (>50 years), as a new soil carbon equilibrium level would be reached. Additional carbon would also be stored in the vegetation itself; estimated to range between 0.3 and 5.6 tCO_2e/ha/year depending on the tree species, harvest frequency and climatic conditions - although higher figures (>15 t tCO_2e/ha/year) have been reported. Additionally, in the longer-term there may be greenhouse gas substitution benefits through the increased use of timber products. CH_4 emissions would be reduced by a small amount (where livestock were previously present).

Key references:

Dawson, J.J.C. and Smith, P. (2006). *Review of Carbon Loss from Soil and its fate in the Environment*. Final report for Defra project SP08010.

Forestry Commission (2003). *Forests and Water Guidelines*. Fourth Edition. Forestry Commission, Edinburgh.

Method 3 – Convert land to biomass cropping (i.e. willow, poplar, miscanthus)

Direction of change for target pollutants on the area of land converted to biomass crops.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓↓	↓↓	↓↓	↓	↓↓	↓*	↓*	↓	↓↓	↓*	↓**

* Only for farmland that previously had livestock.
* Plus enhanced soil carbon storage and biomass carbon sequestration.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✗	✗	✓

Description: Grow perennial biomass crops (e.g. willow, poplar, miscanthus) to displace fossil fuel use, either through direct combustion or through biofuel generation (e.g. by gasification).

Rationale: Cultivation of arable land stimulates the mineralisation of organic matter and release of soil N and carbon. Following the establishment of perennial biomass crops, soils are not cultivated annually which will reduce NO_3 leaching losses compared with conventional arable cropping. Also, lower levels of N fertiliser additions are made to willow, poplar and miscanthus (typically no N is applied in the establishment year and 60-80 kg/ha N per annum thereafter) than most arable and grassland cropping systems, which reduces NO_3 leaching loss risks.

Mechanism for action: Conversion to permanent perennial biomass cropping avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter and manufactured fertiliser N inputs are moderate, thereby reducing the amount of NO_3 that is potentially available for leaching.

Potential for applying the method: The method is applicable to all forms of farmland. It should be noted that a change of land use from arable/grassland food production to energy cropping has implications for the sustainability of food supplies in the UK. i.e. increased use of prime land for energy crop production could lead to greater reliance on food imports and associated overseas greenhouse gas emissions.

Practicality: A change in land use to biomass cropping is unlikely to be adopted by farmers without the provision of suitable financial incentives. Note: Defra's Energy Crop Scheme closed to new applications for establishment grants in June 2006.

Likely Uptake: Low, due to changes to the farming business and *short-term negative cash flow,* unless financial incentives are sufficient.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on planting 25% farmland area (with associated reductions in livestock numbers) and no planting grants. *Note:* Costings are very sensitive to market prices and transport costs.
Annual	-300	-250	-400	-400	-450	-50	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses are likely to be reduced by around 50%. Similarly direct and indirect N_2O emissions and NH_3 emissions would be reduced by around 50%.

P and sediment: Particulate P and associated sediment losses in surface runoff would be reduced by around 50%; provided that best soil management practices were adopted. Soluble P losses would be reduced in the longer-term.

FIOs and BOD: Losses would be reduced by a small amount (where livestock were previously present).

Other pollutants: Where land use change was to permanent biomass cropping, increased soil carbon storage would be in the range 1.9 to 7.0 tCO_2e/ha/year (depending on soil type and previous land use and climate). Additional carbon would also be stored in the biomass itself. The overall long-term effects of large-scale biomass cropping in the UK are unknown. However, the effects of biomass crops such as willow and miscanthus on biodiversity and wildlife value are encouraging (Sage *et al*., 2006), but not entirely clear. CH_4 emissions would be reduced by a small amount (where livestock were previously present).

Key references:

Dawson, J.J.C. and Smith, P. (2006). *Review of Carbon Loss from Soil and its Fate in the Environment*. Final report for Defra project SP08010.

Goodlass, G., Green, M., Hilton, B. and McDonough, S. (2007). Nitrate leaching from short-rotation coppice. *Soil Use and Management,* 23, 178-184.

Johnson, P. (1999). *Fertiliser Requirements for Short Rotation Coppice*. ETSU report B/WZ/00579.REP/1.

Sage, R., Cunningham, M. and Boatman, N. (2006). Birds in willow short-rotation coppice compared to other arable crops in central England and a review of bird census data from energy crops in the UK. *Ibis,* 148, 184-197.

Defra project NT2309 - Nitrate leaching from short rotation coppice following establishment, harvest and crop removal.

Defra project IF0104 - Field-scale impacts on biodiversity from new crops.

Method 4 – Establish cover crops in the autumn

Direction of change for target pollutants on the area occupied by cover crops.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓	↓	↓↓	↓	↓↓	~	~	~	↓	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✗	✓	✗	✗	✗	✗

Description:

- If land would be 'bare' over-winter, establish a cover crop immediately post-harvest or, at the latest, by mid-September. Alternatively, undersow spring crops with a cover crop that would be in place to take up nutrients and provide vegetation cover once the spring crop had been harvested.
- In order to protect the soil surface throughout the period when surface runoff could occur, do not destroy the cover until the land is due to be prepared for the following crop.

Rationale: Without a cover crop, NO_3 can be lost through over-winter leaching and particulate P can be lost through sediment transport in surface runoff. To be effective in reducing NO_3 leaching, the crop needs to take up N before the onset of winter drainage, but thereafter the date of destruction is less critical. To be effective in reducing particulate P and sediment losses the crop does not have to be alive (i.e. straw and crop residues can be effective), but the soil must be protected throughout the period when surface runoff can occur.

Mechanism for action: Cover crops help to reduce NO_3 leaching by taking up N and reduce particulate P losses by protecting the soil from rainfall induced surface runoff and soil erosion. A cover crop will take up soil N (and other nutrients) after the main crop has been harvested in the summer/early autumn, leaving less NO_3 available for leaching over-winter. Ensuring that the land is not left exposed helps reduce surface runoff and soil erosion.

Potential for applying the method: This method is most applicable to tillage land, particularly light soils, where there are significant areas of spring crops. On light soils, a cover crop can be established using cheap methods (e.g. seed broadcasting followed by a light cultivation/rolling). The method is relatively easy to implement for early harvested crops (e.g. vining peas) and is already used in some grassland systems through the undersowing of maize and spring barley with a grass seed mixture. However, difficulties in 'destroying' the cover crop can have implications for following crops.

Practicality: For most autumn-sown arable crops, it is not possible to establish a cover crop that will take up sufficient N to significantly decrease NO_3 leaching losses ahead of sowing the main autumn crop. A cover crop could be broadcast into the main crop before harvest, however, this can damage the standing crop and lead to yield losses. Soil structural damage caused by establishing a cover crop (either late or in wet conditions) may compromise cover crop establishment and result in poor utilisation of soil N by both the cover crop and subsequent crops, and increased particulate P and sediment loss risks. Where cover crops were established as part of the Nitrate Sensitive Area scheme, it was shown to be preferable (for agronomic reasons) to destroy the crop in January or February (at the latest).

Likely uptake: Low-moderate; will depend on the crop rotation and soil type. A moderate level of uptake could be expected on sandy soils and a low level of uptake on medium/heavy soils.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb/ Roots	Costs based on cover crop establishment through cultivations on 70% of spring cropping area.
Annual	400	100	750	3,300	

Effectiveness:

N: NO_3 leaching loss reduction of 30-60% are typical in the year of establishment. Reductions tend to be at the upper end of the range in high fertility situations and/or where manures are regularly applied. Ammonium and nitrite losses to water, and indirect N_2O emissions would also be reduced by a small amount.

P and sediment: Particulate P and associated sediment losses would be reduced; typically in the range 20-80%.

Other pollutants: CO_2 emissions would be increased by a small amount through cover crop establishment.

Key references:

Lord, E.I., Johnson, P.A. & Archer, J.R. (1999). Nitrate Sensitive Areas – a study of large scale control of nitrate loss in England. *Soil Use and Management,* 15, 1-7.

Shepherd, M.A. and Lord, E.I. (1996). Nitrate leaching from a sandy soil; the effect of previous crop and post-harvest soil management in an arable rotation. *Journal of Agricultural Science,* 127, 215-219.

Silgram, M. & Harrison, R. (1998). Mineralisation of cover crop residues over the short and medium term. *Proceedings of the 3rd Workshop of EU Concerted Action 2108 “Long-term reduction of nitrate leaching by cover crops*”, 30 September-3 October 1997, Southwell, UK. AB-DLO, Netherlands.

Defra project NT0402 - To study the use of cover crops in reducing N leaching.

Defra projects NT0401 and NT1508 - To prepare guidelines on the use of cover crops to minimise leaching.

Method 5 – Early harvesting and establishment of crops in the autumn

Direction of change for target pollutants on the area of early harvested land.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	~	~	↓↓	↓	↓↓	~	~	~	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	×	✓	×	×	×	×

Description:

- Harvest crops such as potatoes and maize early (e.g. in September rather than October).
- Establish autumn sown crops earlier (i.e. early October or sooner).

Rationale: Earlier harvesting of crops, especially those that are traditionally harvested late, would enable harvesting to be undertaken when soil conditions were drier, reducing (severe) compaction and soil structural damage risks, and associated sediment and nutrient losses in surface runoff. Establishment of autumn drilled combinable crops by early October would enable the crop to take up (some) N before the onset of over-winter drainage and provide good vegetation cover (at least 25 to 30%) over the winter months to protect the soil from rainfall induced surface runoff and associated erosion.

Mechanism for action: When soils are compacted and there is no growing vegetation to intercept rainfall or take up nutrients, the land is very susceptible to the generation of surface runoff and associated soil erosion. By harvesting/establishing crops early, compaction at harvest would be reduced and the crop would be better established in the autumn to take up N and reduce NO_3 leaching losses.

Potential for applying the method: The method is most applicable to (main crop) potato and maize crops, and maybe applicable to some sugar beet crops.

Practicality: Early harvesting of crops such as maize and potatoes can result in a clash with the harvest of winter cereal crops, creating more work at a time when farmers are already busy.

Likely uptake: Low-moderate. The main disincentive is that harvesting can clash with other harvesting and drilling activities, and potential yield losses due to earlier harvesting.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb/ Roots	Dairy/Grazing Low/Mixed – costs based on no yield loss from early maturing maize varieties. Roots combinable – costs based on a yield loss for potatoes and a small increase in following wheat crop yields (due to earlier establishment in better soil conditions).
Annual	~	~	~	14,800	

Effectiveness:

N: NO_3 leaching losses would be reduced by up to 30% through early winter cereal establishment and associated indirect N_2O emissions.

P and sediment: Particulate P and associated sediment losses would typically be reduced in surface runoff by 20-50%.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Withers, P.J.A. and Bailey, G.A. (2003). Sediment and phosphorus transfer in overland flow from a maize field receiving manure. *Soil Use and Management*, 19, 28-35.

Defra project NT1013 - Phosphorus loss in surface runoff from different land uses.

Defra project NT1033 - Field and farm scale investigation of the mobilisation and retention of sediment and phosphate.

Defra project PE0106 - An environmental soil test to determine potential for sediment & phosphorus transfer in runoff from agricultural land (DESPRAL).

Defra project PE0111 - Towards understanding factors controlling transfer of phosphorus within and from agricultural fields.

Method 6 – Cultivate land for crops in spring rather than autumn

Direction of change for target pollutants on the spring cropped area.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓	↓	↓↓	↓	↓↓	~	~	~	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✗	✗	✓

Description:

- Cultivate arable land for spring crops in spring rather than the autumn.
- Plough out grassland in spring rather than the autumn.

Rationale: Autumn cultivation of land stimulates the mineralisation of N from organic matter reserves at a time when there is little N uptake by the crop, which will increase the potential for over-winter NO_3 leaching losses. By cultivating in spring, there will be less opportunity for mineralised N to be leached and the N will be available for uptake by the established spring crops, and there will be less risk of particulate P losses in surface runoff.

Mechanism of action: The cultivation of soil results in mineralisation of organic N and increases the risk of NO_3 leaching, with the amount of mineralisation strongly affected by soil temperature, moisture and the N balance of the previous crop. In the case of grassland, mineralisation will generally be higher following cultivation of grazed swards than cut swards and will also be higher where more fertiliser N and manure have been historically applied. Autumn cultivation encourages N mineralisation when, in the absence of an actively growing crop, there is little N uptake. Drainage during the following over-winter period then transports the accumulated NO_3 beyond the root zone. Cultivation in spring is better for NO_3 and particulate P losses, because bare soil is not exposed during the over-winter period, and an actively growing crop is established soon after cultivation to take up N and provide surface cover.

Potential for applying the method: This method is mainly applicable to cultivations on light/medium soils prior to the drilling of spring crops (e.g. spring barley, maize, sugar beet, potatoes) or where there is a switch from winter to spring cereal cropping. The method is also applicable to grassland systems where grass leys are ploughed out and re-seeded.

Practicality: Land for spring crops, ploughed in late autumn, has the winter for frost action and wetting and drying cycles to break down soil clods (particularly on medium/heavy soil types). Ploughing in the autumn also allows early establishment of the following spring crop, as only secondary cultivations are required ahead of drilling. On medium/heavy soils, if ploughing is not carried out in late autumn/early winter, delaying cultivations until spring can result in the spring crop being drilled into a drying seedbed, which can impact on crop establishment and yields, and poor utilisation of applied manufactured fertiliser and/or manure N. Delaying cultivation until the spring may also have implications for the control of some weeds. There are also soil structural implications associated with cultivations in a wet spring, particularly on medium/heavy soils. For grassland, reseeding in spring is less reliable than in autumn.

Likely uptake: Low-moderate on light/medium soils. On medium/heavy soils, uptake will be low due to farmer concerns over crop establishment/weed problems and the potential for crop yield losses.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on yield losses in spring sown arable crops and grassland.
Annual	300	100	1,400	1,100	3,600	1,500	

Effectiveness:

N: NO_3 leaching losses would typically be reduced by 20-50%; on arable land with manure the reduction is likely to be at the higher end of the range. Indirect N_2O emissions would be reduced by a small amount.

P and sediment: Particulate P and associated sediment losses in surface runoff would typically by reduced by 20-50%.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Johnson, P.A., Shepherd, M.A., Hatley, D.J. and Smith P.N. (2002). Nitrate leaching from a shallow limestone soil growing a five course combinable crop rotation: the effects of crop husbandry and nitrogen fertiliser rate on losses from the second complete rotation. *Soil Use and Management*, 18, 68-76.

Silgram, M. & Shepherd, M.A. (1999). The effect of cultivation on soil nitrogen mineralisation. *Advances in Agronomy*, 65, 267-311.

Defra project NT1829 - Further N cycle studies on farmlets.

Method 7 – Adopt reduced cultivation systems

Effect on target pollutants where inversion (ploughed) tillage was used previously.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓↓	(↓)	↓↓	~	~	~	(↑)	~	↓*

( ) Uncertain.
* Plus enhanced soil carbon storage.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✗	✗	✗

Description:

- Reduced cultivations, using discs or tines, to cultivate the soil surface as the primary cultivation in seedbed preparation (typically 10-15cm cultivation depth).
- Direct drilling or broadcasting of seed (i.e. no-till).

Rationale: Reduced/no-till cultivations (rather than ploughing) can retain soil surface organic matter and preserve good soil structure, with the resulting soil conditions improving water infiltration rates and thereby reducing loss risks of particulate P and sediment.

Mechanism of action: Maintaining good soil structure and improving water infiltration rates reduces soil erosion risks; large reductions in surface runoff can be achieved where a mulch of crop residues is left on the surface. NO_3 leaching is generally decreased as there is less soil disturbance and hence less organic matter mineralisation.

Potential for applying the method: This method has already been adopted on a large number of arable farms, with around 1.5 million hectares already cultivated using discs or tines. It is most commonly used on medium/heavy soils, although reduced cultivations are increasingly being carried out on light soils. It is less likely to be adopted in wetter parts of the country. In the UK, intermittent ploughing (typically every 3-4 years) is usually part of farm cultivation systems, as a means of minimising compaction near the soil surface and for rotational weed control.

Practicability: Reduced cultivation systems are less appropriate in wet autumns and only suitable where soil structural problems have been alleviated. Reduced cultivations may increase resistant weed populations and therefore increase reliance on agro-chemical control. The incorporation of large volumes of straw into a small volume of soil (as part of a reduced cultivation system) may immobilise N and create a small need for additional N application. No-till is generally unsuitable for light soils that are prone to capping.

Likely uptake: The largest barrier to uptake is likely to be the purchase of new machinery (in addition to those outlined above) and so is most likely to be adopted on larger combinable crop farms.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Savings are due to reduced cultivation costs.
Annual	-150	-150	-1300	-4,300	-3,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching loss reductions can be up to 20%; reductions are likely to be at the higher end where manures are applied. Indirect N_2O emissions would also be reduced, however, there is some evidence of higher direct N_2O emissions from reduced/no-till land.

P and sediment: Particulate P and associated sediment loss reductions can be up to 60% on medium/heavy soils and up to 90% on light soils.

Other pollutants: CO_2 emissions would be reduced as a result of the lower power requirements of reduced/no-till cultivation. Soil carbon storage would be increased by a small amount typically 0.57 tCO_2e/ha/year for reduced tillage and 1.14 tCO_2e/ha/year for no-till.

Key references:

Bhogal, A., Chambers, B.J., Whitmore, A. and Poulson, D.S. (2008). *The Effects of Reduced Tillage Practices and Organic Material Additions on the Carbon Content of Arable Soils*. Final report for Defra project SP0561, 47pp.

Chambers, B.J., Bhogal, A., Whitmore, A.P. and Poulson, D. (2008). The potential to increase carbon storage in agricultural soils. In: *Land Management in a Changing Environment* – Proceedings of the SAC and SEPA Biennial Conference, (Eds. K. Crighton and R. Audsley), pp.190-196.

Johnson, P.A., Shepherd, M.A., Hatley, D.J. and Smith P.N. (2002). Nitrate leaching from a shallow limestone soil growing a five course combinable crop rotation: the effects of crop husbandry and nitrogen fertiliser rate on losses from the second complete rotation. Soil Use and Management, 18, 68-76.

Lord, E.I., Shepherd, M.A., Silgram, M, Goodlass, G., Gooday, R, Anthony, S.G., Davison, P. and Hodgkinson, R. (2007). *Investigating the Effectiveness of NVZ Action Programme Measures: Development of a Strategy for England*. Final report for Defra Project NIT18.

Silgram, M. and Shepherd, M.A. (1999). The effect of cultivation on soil nitrogen mineralisation. *Advances in Agronomy*, 65, 267-311.

Defra project PE0206 - Field testing of mitigation options (MOPS1).

Method 8 – Cultivate compacted tillage soils

Direction of change for target pollutants on tillage land.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	↓↓	↓	↓↓	~	~	~	(↓)	~	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	✓	✓	×	×	×	✓

Description:

- Cultivate compacted tillage soils to increase aeration and water infiltration rates.
- Endeavour to establish a vegetative cover from a drilled crop, through natural regeneration or broadcast (barley) seed.

Rationale: Cultivation disrupts compaction, increases surface roughness and water infiltration rates. The method will reduce particulate P and associated sediment losses.

Mechanism of action: The method reduces surface runoff and soil erosion. When soils are compacted or capped and there is little crop residue or vegetation cover to intercept rainfall, soils can be susceptible to surface runoff. Cultivation of the soil surface (during dry conditions) will increase surface roughness, which will enhance water infiltration rates into the soil and reduce surface runoff volumes.

Potential for applying the method: The method is applicable to all tillage land where soils are compacted, and particularly sloping land in high rainfall areas.

Practicability: The cultivation itself is straightforward. However, for the method to be effective it should be carried out when soils are dry.

Likely uptake: If compaction is identified as an issue it is likely to be alleviated by farmers.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Based on a cultivation cost of £25/ha (on 20% of the tillage land area each year).
Annual	100	50	500	1,500	1,600	150	

Effectiveness:

N: There may be a small reduction in direct N_2O emissions, as a result of increased soil aeration.

P and sediment: Particulate P and associated sediment loss reductions would typically be in the range 10 and 50%.

Other pollutants: CO_2 emissions would be increased by a small amount from the additional cultivation. Impacts on other pollutants are likely to be minimal.

Key references:

Catt, J.A., Howse, K.R., Farina, R., Brockie, D., Todd, A., Chambers, B.J., Hodgkinson, R., Harris, G.L. and Quinton, J.N. (1998). Phosphorus losses from arable land in England. *Soil Use and Management*, 14, 168-174.

Chambers, B.J., Garwood, T.W.D. and Unwin, R.J. (2000). Controlling Soil Water Erosion and Phosphorus Losses from Arable Land in England and Wales. *Journal of Environmental Quality*, 29 145-150.

Defra project PE0206 - Field testing of mitigation options (MOPS1).

Method 9 – Cultivate and drill across the slope

Direction of change for target pollutants on sloping land.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	↓↓	↓	↓↓	~	~	~	~	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✗	✗	✓

Description: Cultivate and drill land along the slope (contour) to reduce the risk of developing surface runoff.

Rationale: On fields with *simple slope patterns*, cultivating and drilling across the slope will reduce the risk of surface runoff being initiated and increase re-deposition rates where surface runoff does occur. The ridges created across the slope increase down-slope surface roughness and provide a barrier to surface runoff. As a result, particulate P and associated sediment losses will be reduced.

Mechanism of action: Cultivating across the slope reduces the risk of developing surface sheet and rill flow. Furrows (and tramlines) orientated down the slope will tend to collect water and develop concentrated surface flow paths; this risk can be reduced if they are aligned across the slope.

Potential for applying the method: Applicable to all cultivated soils where fields have simple slope patterns.

Practicability: The method is more time-consuming and requires greater skill than conventional field operations. Cultivations and drilling should not be carried out across very steep slopes, due to the risk of machinery overturning. Also, as indicated in the Defra “Code of Good Agricultural Practice (2009)”, this method is only likely to be effective for crops grown on gently and moderately sloping fields, with simple slope patterns. For steeper sloping fields with complex slope patterns, it is not practical to follow slopes (contours) accurately. In these fields, attempts at cultivation across the slope often leads to channelling of surface runoff waters, particularly in tramlines or wheelings, which can cause severe (gully) erosion on headlands. For furrow crops, such as potatoes and sugar beet, harvesters only work effectively up and down the slope. It may be more effective to stop growing such crops on steeply sloping areas or to use ‘tied ridges’ to reduce runoff.

Likely uptake: Uptake is most likely on fields with gentle/moderate slopes and simple slope patterns, and that are longer across slope than in the upslope direction.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on additional management time (£10/ha) and applied to 30% of tillage land area.
Annual	50	20	150	450	500	50	

Effectiveness:

P and sediment: Limited evidence indicates that cultivating/drilling across the slope can reduce particulate P and associated sediment losses by 40-80%.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Defra (2009). *A Code of Good Agricultural Practice for Farmers, Growers and Land Managers*. The Stationery Office, Norwich. ISBN 978-0-11-243284-5.

Quinton, J.N. and Catt, J.A. (2004). The effects of minimal tillage and contour cultivation on surface runoff, soil loss and crop yield in the long-term Woburn Erosion Reference Experiment on sandy soil at Woburn, England. *Soil Use and Management,* 20, 343-349.

Defra project PE0206 - Field testing of mitigation options (MOPS1)

Method 10 – Leave autumn seedbeds rough

Direction of change for target pollutants on winter cereal area.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	↓	~	↓	~	~	~	~	~	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	✓	✓	×	×	×	×

Description: Avoid creating a fine autumn seedbed that will ‘slump’ and run together.

Rationale: Leaving the autumn seedbed rough encourages surface water infiltration and reduces the risk of surface runoff, thereby reducing particulate P and associated sediment loss risks.

Mechanism of action: A more open seedbed is created by using a reduced number of cultivations, particularly from powered cultivation equipment and by avoiding use of a heavy roller. This helps to reduce the risk of surface runoff by preventing soil capping and enhancing surface water infiltration into the soil. A rough seedbed also helps to break up any surface flow that is generated, reducing the risk of sheet wash and rill erosion.

Potential for applying the method: Applicable to the establishment of ‘large’ seeded crops on tillage land (particularly on light soils). It is most applicable to winter cereal crops that can establish well in coarse seedbeds. However, ‘patchy’ crop establishment (or indeed crop failure) would reduce yields and lead to an increased risk of sediment losses from bare soils over-winter and could increase NO_3 leaching in the following over-winter period.

Practicability: Herbicide activity is most effective in firm and fine seedbeds; rough seedbeds can reduce activity. The method is not well suited to ‘small’ seeded crops such as oilseed rape, sugar beet and grass that require fine, clod-free seedbeds. *A rough seedbed may not be appropriate when there is a high risk of slug damage*.

Likely uptake: Low, due to pest (particularly slug) and weed control issues.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Costs based on additional pest/weed control inputs and ‘poorer’ crop establishment on 50% of winter cereal area.
Annual	200	100	500	2,500	1,500	

Effectiveness:

P and sediment: Limited field evidence indicates that particulate P and associated sediment losses can be reduced by up to 20%.

Other pollutants: CO_2 emissions would be reduced by a small amount from less cultivation. Impacts on other pollutants are likely to be minimal.

Key reference:

Defra project PE0206 - Field testing of mitigation options (MOPS1)

Method 11 – Manage over-winter tramlines

Direction of change for target pollutants on tillage land area with tramlines.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	↓↓	↓	↓↓	~	~	~	~	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	✓	✓	×	×	×	×

Description: Use tines to disrupt tramlines or delay their establishment until the spring.

Rationale: Tramlines are generally established in autumn sown combinable crops at the time of drilling; they can result in the channelling of surface water and the development of rills and gullies on sloping erosion susceptible soils. Tramline management to improve water infiltration rates can help to reduce accelerated runoff and the loss of particulate P/sediment.

Mechanism of action: Avoiding the use of over-winter tramlines helps prevent surface runoff and associated sediment mobilisation, as ‘compacted’ tramlines can act as concentrated flow pathways during periods of increased surface runoff. If tramlines are present, for example, as a result of the need to apply agro-chemicals during the autumn period, then tines can be used to disrupt the tramlines, which encourages water to infiltrate into the soil. Using low ground-pressure vehicles also helps to limit soil compaction and maintain water infiltration rates.

Potential for applying the method: This method (either avoiding or disrupting tramlines) is applicable to winter cereal cropped land, particularly on light/medium textured soils on sloping land in higher rainfall areas.

Practicability: Not establishing over-winter tramlines is potentially applicable to all winter sown combinable crop land, but is less applicable to oilseed rape crops due to the (common) need to apply agro-chemical in autumn/winter.

Likely uptake: Low-moderate.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Costs based on additional tine cultivation of tramlines (on 30% of tillage land area).
Annual	10	20	150	750	400	

Effectiveness:

P and sediment: Limited field evidence indicates that tramline disruption can reduce particulate P and associated sediment losses by 30-50% on winter cereal cropped land.

Other pollutants: CO_2 emissions would be increased by a small amount from the additional tine cultivation. Impacts on other pollutants are likely to be minimal.

Key references:

Chambers, B.J. and Garwood, T. (2000). Monitoring of water erosion on arable farms in England and Wales: 1989-1990. *Soil Use and Management,* 8, 163-170.

Silgram, M., Jackson, B., Quinton, J., Stevens, C. and Bailey, A. (2007). Can tramline management be an effective tool for mitigating phosphorus and sediment loss? *Proceedings of the 5th International Phosphorus Transfer Workshop (IPW5)*, 3-7 September 2007, Silkeborg, Denmark (ed. G. Heckrath, G. Rubaek and B. Kronvang). pp 287-290. ISBN 87-91949-20-3.

Withers, P.J.A., Hodgkinson, R.A., Bates, A. and Withers C. (2006). Some effects of tramlines on surface runoff, sediment and phosphorus mobilization on an erosion-prone soil. *Soil Use and Management,* 22, 245-255.

Defra project PE0206 - Field testing of mitigation options (MOPS1).

Method 12 – Maintain and enhance soil organic matter levels

Direction of change for target pollutants on arable land receiving organic manures.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	(↓↑)	↑	↓	↑	↑	↑	↑	~	↑*

( ) Uncertain.
* Plus enhanced soil carbon storage.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✗	✗	✗	✗	✓	✓	✗	✗	✗	✓

Description: Maintain and enhance soil organic matter levels by the regular addition of organic materials (e.g. livestock manures, biosolids, compost, digestate) and retention of crop residues.

Rationale: Low soil organic matter levels are a concern in some arable systems; they can give rise to soil structural problems and increased risks of soil erosion. Maintaining and enhancing soil organic matter levels helps to reduce the risks of surface runoff and erosion, enables improved water retention and the efficient use of soil and added nutrients. The long-term benefits of improved soil structure etc. should be effective in reducing particulate P and associated sediment losses.

Mechanism of action: Maintaining soil organic matter levels helps to maintain good soil structure, fertility and aggregate stability. Good structure enhances the infiltration, retention and movement of water through the soil, and improved soil microbial activity helps to increase plant nutrient uptake from soil reserves. Well-structured soils are more easily cultivated, resulting in more uniform crop establishment and growth and associated nutrient uptake (particularly N). To minimise soil P accumulation (and associated soluble P losses) and mineral N levels in the soil, it is important that the implementation of this method is accompanied by a reduction in manufactured fertiliser use to take account of the additional nutrients supplied by the organic materials (or crop residues).

Potential for applying the method: This method is applicable to all arable farming systems; particularly on low organic matter soils that are structurally unstable.

Practicability: Depends on the local availability of organic materials. Where the farm is in a Nitrate Vulnerable Zone (NVZ), the application of organic materials, must comply with NVZ Action Programme field N application rate limit and ‘closed spreading periods for high readily available N materials (e.g. slurry, poultry manure and digestate).

Likely uptake: Moderate-high, due to the increasing cost of manufactured fertilisers and importance of organic matter supply to arable soils.

Cost:

Total *cost* for farm system (£/farm)	Comb Crops	Comb/ Roots	Hort	Costs based on the receiving farm paying the transport cost of the organic materials from 3 km and 10 km distances.
Annual @3km	-6,500	-6,800	-350	
Annual @10km	800	850	50	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be increased, particularly where high readily available manures are applied in the autumn period (by up to 20% of total N applied). Similarly direct and indirect N_2O emissions and NH_3 emissions would be increased. However, manufactured fertiliser N inputs would be reduced.

P and sediment: Particulate P and associated sediment loss reductions would be expected through building up organic matter reserves and better soil structure over a period of years. However, there would be an increased risk of incidental P losses from the added organic materials, particularly where rainfall occurs soon after the application of slurry to ‘wet’ soils.

FIOs and BOD: Losses would be increased by a small amount from the organic material applications.

Other pollutants: CO_2 emissions would be increased by a small amount through transporting and applying the organic materials.

Key references:

Bhogal, A., Chambers, B.J., Whitmore, A. and Poulson, D.S. (2008). *The Effects of Reduced Tillage Practices and Organic Material Additions on the Carbon Content of Arable Soils*. Final report for Defra project SP0561, 47pp.

Chambers, B.J., Bhogal, A., Whitmore, A.P. and Poulson, D. (2008). The potential to increase carbon storage in agricultural soils. In: *Land Management in a Changing Environment* – Proceedings of the SAC and SEPA Biennial Conference, (Eds. K. Crighton and R. Audsley), pp.190-196.

Defra project NT1831 - The effect of organic manures on medium-term N cycling and nitrate leaching.

Defra project NT1835 - The effects of manure application to land on N loss pathways to air and water

Defra project OF0164 - Understanding soil fertility in organically farmed systems.

Defra project SP0530 - Organic Manure and Crop Organic Carbon Returns - Effects on Soil Quality (Soil-QC).

Defra project ES0106 - Developing integrated land use and manure management strategies to control diffuse nutrient losses from drained clay soils: BRIMSTONE-*NPS*.

Method 13 – Establish in-field grass buffer strips on tillage land

Direction of change for target pollutants in tillage fields where buffer strips established.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓↓	↓	↓↓	~	~	~	↓	~	↓*

* Plus enhanced soil carbon storage.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✓	✗	✓

Description: On sloping tillage fields and outdoor pig land, establish (unfertilised) grass buffer strips along the land contour, in valley bottoms or on upper slopes to reduce and slow down surface runoff.

Rationale: In-field grass buffer strips can reduce particulate P and associated sediment losses by slowing surface runoff and intercepting sediment delivery.

Mechanism of action: An in-field grass buffer strip is a vegetated area of land, located along the land contour, on upper slopes or in valley bottoms; it is usually a permanent feature, although it can be temporary. Both the Entry Level and Higher Level Environmental Stewardship (ELS/HLS) schemes have options to establish in-field grass areas to prevent surface runoff and erosion. Buffer strips can also act as a sediment-trap, helping to reduce nutrient and other associated losses in surface runoff.

Potential for applying the method: In-field buffer strips are applicable to all arable farming systems, particularly on sloping land. They are particularly suited to fields with long slopes where high volumes of surface runoff can be generated.

Practicability: Buffer strips require ‘investment’ to establish, but once established they generally require little maintenance. They reduce the length of fields and can increase the time taken for field operations, but are generally well accepted by farmers who are keen to improve the environmental potential of their farm. They are most effective when combined with additional riparian buffer strips (Method 14). Buffer strips are less effective where they are compacted as a result of use by vehicles, and there can be issues with weed control; hence they should (generally) be cut.

Likely uptake: Low-moderate; ‘poor’ patches are ideal for buffer strips. Farmers are less likely to establish buffers along the midslope contour, unless financial incentives are available (e.g. through ELS/HLS).

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Out Pigs	Hort	Costs based on crop yield losses and topping management (buffer strips assumed to occupy 1% of tillage/outdoor pig farm area).
Annual	1,000	50	500	800	3,500	1,200	1,000	

Effectiveness:

N: NO_3 leaching loss reductions from the strip area would be similar to that from ungrazed/zero-N grassland i.e. around a 90% reduction; annual losses from converted land would typically by <5 kg N/ha (see Methods 1A/B). Ammonium and nitrite losses would also be reduced by a small amount. Similarly, direct and indirect N_2O emissions would be reduced, as manufactured fertiliser N would not be applied to the buffer strips.

P and sediment: Particulate P and associated sediment losses reductions would typically be in the range 20-80%.

Other pollutants: CO_2 emissions would be reduced from the un-farmed strips and soil carbon storage increased (see Methods 1A/B). Impacts on other pollutants are likely to be minimal.

Key references:

Dillahar, T.A. and Inamadar, S.P. (1997). Buffer zones as sediment traps or sources. In: Haycock, N.E., Burt, T.P., Goulding, K.W.T. and Pinay, G. (Eds.) *Buffer Zones: Their Processes and Potential in Water Quality Protection.* Quest Environmental, Harpenden, UK, pp. 33-42.

Muscutt, A.D., Harris, G.L., Bailey, S.W. and Davies, D.B. (1993). Buffer zones to improve water quality: a review of their potential use in UK agriculture. *Agriculture, Ecosystems and Environment,* 45, 59-77.

Defra project PE0206 - Field testing of mitigation options (MOPS1).

Method 14 – Establish riparian buffer strips

Direction of change for target pollutants in fields when riparian buffer strips established.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓↓	↓	↓↓	↓*	↓*	~	↓	~	↓**

* Where livestock were previously present/manures spread.
** Plus enhanced soil carbon storage.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✓	✗	✓

Description: Establish vegetated (and unfertilised) grass/woodland buffer strips alongside watercourses.
Rationale: The grass/woodland strip will act as a 'natural' buffer feature to reduce the transfer of pollutants from agricultural land to water.
Mechanism of action: Riparian buffer strips can reduce pollution delivery in two ways. They distance agricultural activity from watercourses and therefore reduce direct pollution from fertiliser and organic manure additions, and can restrict direct livestock access to watercourses. They can also intercept surface runoff from agricultural land before it reaches the watercourse, therefore acting as a sediment trap and filter for nutrients.
Riparian strips should ideally be free-draining and have a good surface porosity to intercept surface runoff. The Entry Level Environmental Stewardship scheme offers options for buffer strips between 2 and 6 m in width, and 10 m around in-field ponds.
Potential for applying the method: Riparian buffer strips are most effective at retaining sediment when overland flow is shallow and slow; they are particularly suited to low-lying and gently undulating landscapes where the topography does not concentrate the flow into channels. The effectiveness of riparian buffers is dependent upon their design and implementation, the density of the vegetation, the species used and the age of the buffer itself. They are potentially applicable to all farming systems where watercourses are present.
Practicability: Riparian strips require a certain amount of 'investment' to establish, but once established generally require little maintenance. They are generally well accepted by farmers who are keen to improve the environmental potential of their farm, but there can be issues with weed control from the strips. Buffer strips are less effective where they are compacted as a result of use by vehicles.
Likely uptake: Medium; 'poor' field area at the waters edge are ideal. The establishment of riparian areas is less likely on 'better' land, unless financial incentives are available (through ELS or other schemes).
Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Out Pigs	Hort	Costs based on loss of gross margin (on 3% of farmed area), plus establishment and topping costs, and fencing in grassland fields.
Annual	3,400	650	2,300	2,400	10,600	4,500	2,800	

Effectiveness:
N: NO_3 leaching loss reductions from the strip area would be the same as from ungrazed/zero–N grassland i.e. around a 90% reduction; annual losses from converted land would typically be <5 kg N/ha (see Methods 1A/B). Ammonium and nitrite losses would also be reduced by a small amount. Similarly, direct and indirect N_2O emissions would be reduced, as manufactured fertiliser N would not be applied to the riparian strips.
P and sediment: Particulate P and associated sediment losses would typically be reduced by 20-80%.
FIOs and BOD: Losses would be reduced by a small amount (where livestock were previously present).
Other pollutants: CO_2 emissions would be reduced from the un-farmed strip and soil carbon storage increased (see Methods 1A/B)

Key references:

Muscutt, A.D., Harris, G.L., Bailey, S.W. and Davies, D.B. (1993). Buffer zones to improve water quality: a review of their potential use in UK agriculture. *Agriculture, Ecosystems and Environment,* 45, 59-77.

Defra project PE0205 - Strategic placement and design of buffering features for sediment and P in the landscape.

Method 15 – Loosen compacted soil layers in grassland fields

Direction of change for target pollutants in loosened grassland fields.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	↓↓	~	↓↓	↓	↓	↓*	↓	~	↑

* Where slurry applied.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✗	✗	✗	✗

Description: Reduce surface runoff from grassland fields by loosening to disrupt compacted soil layers, as required in relation to the depth of soil compaction. These operations should be carried out in moist soil conditions so as not to damage the grass sward.

Rationale: Compacted soil layers reduce the infiltration of rainwater and slurry into the soil. Disrupting these compacted layers allows more rapid percolation of rainwater/slurry into the soil and reduces the risk of pollutants being transported to watercourses in surface runoff.

Mechanism of action: Trampling by livestock (both cattle and sheep) and the passage of heavy farm machinery can compact grassland soils in both grazing and silage fields. Compaction may build-up over a number of years and persist in the long-term. Topsoil loosening and shallow spiking/slitting can break up compacted layers and allow more rapid rainwater and slurry infiltration, thus reducing surface runoff. In addition, soil aeration can be improved and result in roots being able to penetrate deeper into the soil, which will increase nutrient uptake from deeper soil layers.

Potential for applying the method: The method is potentially applicable to all grassland farms, but particularly those with high stocking rates.

Likely uptake: Moderate to high on fields where soil compaction has been identified.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Based on a loosening cost of £40/ha (applied to 25% of grassland area).
Annual	1,000	1,500	1,000	1,000	

Effectiveness:

N: Effects on NO_3 leaching losses are likely to be minimal. As a result of improved soil aeration direct N_2O emissions are likely to be reduced, and as a result of improved soil infiltration rates NH_3 emissions are likely to be reduced following slurry application.

P and sediment: Particulate P and associated sediment losses would typically be reduced by 10-50%.

FIOs and BOD: Losses would be reduced by a small amount.

Other pollutants: CO_2 emissions would be increased by a small amount through the loosening operation.

Key references:

Heathwaite, A.L., Burt, T.P. and Trudgill, S.T. (1990). Land-use Controls on Sediment Production in a Lowland Catchment, South-west England. In: J. Boardman, I.D.L. Foster and J.A. Dearing (Editors), *Soil Erosion on Agricultural Land*. John Wiley and Sons Ltd., Chichester, UK.

Ruser R., Flessa H., Russow R., Schmidt G., Buegger F. & Munch J.C. (2006). Emission of N_2O, N_2 and CO_2 from soil fertilised with nitrate: effect of compaction, soil moisture and rewetting. *Soil Biology and Biochemistry*, 38, 263-274.

Yamulki S. & Jarvis S. C. (2002) Short-term effects of tillage and compaction on nitrous oxide, nitric oxide, nitrogen dioxide, methane and carbon dioxide fluxes from grassland. *Biology and Fertility of Soils*, 36, 224-231.

Method 16 – Allow field drainage systems to deteriorate

Direction of change for target pollutants on soils with artificial under drainage.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	(↓)	(↓)	(↓)	~	(↓)	(~)	(~)	~	↑	~	~

( ) Uncertain.

Change arrows apply to grassland.

Note: Maintenance of an effective drainage system is taken as 'baseline' management for arable land, as without an effective drainage system, economically sustainable arable cropping would not be possible on most medium/heavy soils.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✗	✗	✗	✗

Description:

- Allow existing (old) drainage systems to naturally deteriorate i.e. cease to maintain them.
- Some drainage systems will survive for decades with little management, therefore this can be a long-term option.

Rationale: Drainage systems can accelerate the delivery of pollutants from land to a watercourse, by acting as a preferential (by-pass) flow route. Allowing drainage systems to deteriorate therefore reduces hydrological connectivity and the potential transfer of pollutants to watercourses, although surface runoff would be increased.

Mechanism of action: When drains have deteriorated, water is forced to percolate through the soil at a slower rate, which increases the opportunity for the retention (or transformation) of potential pollutants through physical filtration and biological activity in the soil. Allowing drains to deteriorate will result in a higher water table being maintained, thereby reducing N mineralisation from soil organic matter and NO_3 leaching, but will potentially increase the risk of incidental losses in surface runoff.

Potential for applying the method: There are around 6 million hectares of drained soils in England and Wales. This method is most applicable to the grassland sector on medium/heavy soils. It is a relatively easy option to implement, but is unlikely to be popular with farmers, particularly where waterlogging is a problem. Undrained grassland will wet up earlier in autumn so that stock need to be removed earlier to avoid poaching. *Excess water and waterlogging in parts of fields may lead to poor crop establishment, restricted nutrient uptake and will increase soil compaction risks; minimising soil compaction is cross-compliance requirement of the Single Payment Scheme.* Drainage deterioration is compatible with the Higher Level Environmental Stewardship Scheme, where farmers may be able to obtain payment for restoring traditional water meadows.

If the drainage status deteriorated greatly, it is likely that a farmer would revert the arable land to grassland or on other alternative land use (see Methods 1A/B; 2; 3).

Practicability: The method is easy to implement as no action is necessary. However, there would be considerable resistance from farmers to adopting the method as a deliberately managed activity, without financial incentive. It is also probable that with increasing soil wetness, it would be necessary to either reduce the length of the grazing season (Method 35) or reduce stocking rates on livestock farms (Method 37). In many grassland areas, the deterioration of field drainage systems is probably occurring in practice, because farmers do not have the funds to replace ageing systems.

Likely uptake: Low, without financial incentives. It is highly unlikely that farmers would deliberately allow drainage systems to deteriorate, due to the large impact this can have on production.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs based on loss of production due to poor drainage.
Annual	1,200	450	900	2,500	

Effectiveness:

N: NO_3 leaching loss reductions would typically be in the range of 10-50%, with reductions at the upper end of the range from higher input grassland systems. Ammonium and nitrite losses would also be reduced, and indirect N_2O losses as a result of lower NO_3 leaching losses. However, direct N_2O emissions would be increased as a result of greater soil wetness and associated denitrification losses.

P and sediment: Particulate P and associated sediment losses would typically be reduced by up to 10%, provided that livestock were removed when the soil was wet i.e. that poaching was not increased.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Ruser R., Flessa H., Russow R., Schmidt G., Buegger F. & Munch J.C. (2006). Emission of N_2O, N_2 and CO_2 from soil fertilised with nitrate: effect of compaction, soil moisture and rewetting. *Soil Biology and Biochemistry*, 38, 263-274.
Withers, P.J.A., Davidson, I.H. and Roy, R.H. (2000). Prospects for controlling non-point phosphorus losses to water: A UK perspective. *Journal of Environmental Quality*, 29, 167-175.
Defra project NT1012 - Phosphate loss from cracking clay soils.
Defra project ES0106 - Developing integrated land use and manure management systems to control diffuse nutrient losses from drained clay soils: BRIMSTONE-*NPS*.

Method 17 – Maintain/improve field drainage systems

Direction of change for target pollutants on soils with artificial under drainage.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑↑	(↑)	(↑)	(↑)	~	(↑)	(~)	(~)	~	↓	~	↑

( ) Uncertain.

Change arrows apply to grassland.

Note: Maintenance of an effective drainage system is taken as 'baseline' management for arable land, as without an effective drainage system, economically sustainable arable cropping would not be possible on most medium/heavy soils.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✗	✓

Description: Actively maintain field drainage systems through jetting, re-installation and renewed moling.

Rationale: A functioning drainage system ensures that water is able to move through the soil profile, allowing the soil to be maintained in a 'well drained' condition and extending the window of opportunity for machinery operations and livestock grazing, particularly in autumn and spring. Maintaining field drainage systems minimises the risk of poaching, compaction and waterlogging, and can reduce surface runoff; an important pathway for the loss of particulate P and sediment (particularly from tillage land).

Mechanism for action: The method reduces the period when soils are at risk from compaction and poaching, and reduces the risk of surface runoff and associated particulate P/sediment losses. However, drainflow losses of nutrients (particularly NO_3 and P) are likely to be increased.

Potential for applying the method: The method is applicable to all drained fields, particularly on medium/heavy soils types and in grassland farming systems. The Method is inter-linked with Method 18 (ditch maintenance).

Practicality: The method is relatively easy to apply, assuming that the drainage system has not already deteriorated. In most circumstances, a functioning drainage system would result in better crop yields and increased nutrient uptake.

Likely uptake: High, mainly due to the impact that poor drainage can have on crop production and management versatility of the land.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on moling 20% of the farm each year, as a 'proxy' cost for maintaining drainage systems (no yield increases have been included).
Annual	350	50	200	750	1,500	1,650	150	

Effectiveness:

N: On grassland, NO_3 leaching losses would typically be increased by 10-50% compared with drainage deterioration. Ammonium and nitrite losses would also be increased and indirect N_2O losses as a result of higher NO_3 leaching losses. However, direct N_2O emissions would be decreased as a result of more aerobic soils conditions and lower denitrification losses.

P and sediment: Particulate P and associated sediment losses would typically be increased by up to 10%, as a result of greater drainflow losses.

Other pollutants: CO_2 emissions would be increased by a small amount from the moling operation. Impacts on other pollutants are likely to be minimal.

Key references:

Ruser R., Flessa H., Russow R., Schmidt G., Buegger F. & Munch J.C. (2006). Emission of N_2O, N_2 and CO_2 from soil fertilised with nitrate: effect of compaction, soil moisture and rewetting. *Soil Biology and Biochemistry*, 38, 263-274.

Defra project NT1012 - Phosphate loss from cracking clay soils.

Defra project ES0106 - Developing integrated land use and manure management systems to control diffuse nutrient losses from drained clay soils: BRIMSTONE-*NPS*.

Method 18 – Ditch management

Direction of change for target pollutants on the area of the farm with ditches.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	↑	~	↑	~	~	~	↓	~	↑

Note: The assessment below assumes that ditches are not well managed before method implementation.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✓	✗	✓

Description: Clear out ditches on a regular basis to ensure field drainage systems are able to function. This may include cutting vegetation in the bottom of the ditch to prevent flooding.

Rationale: To ensure a drainage system functions at its optimum the water needs to be able to exit the ditch system. Clearing out ditches will achieve this.

Mechanism for action: This method will allow field drainage systems to function thereby reducing the risk of waterlogging, soil compaction, poaching and surface runoff.

Potential for applying the method: The method is applicable to all farms with ditches and a drainage system. This method is inter-linked with Method 17 – 'maintain/improve field drainage systems'.

Practicality: The method is relatively easy to apply, assuming that access to the ditch is straightforward. In most circumstances, a functioning ditch/drainage system will result in better crop yields and improved nutrient uptake.

Likely uptake: High, mainly due to the impact that poor drainage (and localised flooding) can have on crop production and the management versatility of land.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Out Pigs	Hort	Costs based on each field having a ditch on one side and that 20% of ditches are cleaned each year.
Annual	400	300	350	550	550	600	200	50	

Effectiveness:

N: NO_3 leaching losses would typically be increased by up to 20%. Ammonium and nitrite losses would also be increased and indirect N_2O losses as a result of higher NO_3 leaching losses. However, direct N_2O emissions would be decreased as a result of more aerobic soil conditions and lower denitrification losses.

P and sediment: Particulate P and associated sediment losses would typically be increased by up to 10%, and as a result of increased drainflow losses.

Other pollutants: CO_2 emissions would increase by a small amount as a result of the ditch cleaning operation. Impacts on other pollutants are likely to be minimal.

Key references:

Ruser, R., Flessa, H., Russow, R., Schmidt, G., Buegger, F. & Munch J.C. (2006). Emission of N_2O, N_2 and CO_2 from soil fertilised with nitrate: effect of compaction, soil moisture and rewetting. *Soil Biology and Biochemistry*, 38, 263-274.

Method 19 – Make use of improved genetic resources in livestock

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	~	~	↓	↓	↓	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	×	×	×	×

Description: Use genetic resources to improve lifetime efficiency of livestock systems.

Rationale: The selection of useful traits that relate to improved animal robustness (e.g. health, fertility) can result in:

- Increased efficiency of individual animals.
- Increased longevity (including calving ease for dairy cows), fertility and other non-yield traits.

For the last few decades selection goals have focussed more on animal production characteristics than on health and robustness characteristics. While this approach has achieved large advances in animal production (meat, milk and eggs), other beneficial heritable traits were largely deemed to be of lesser importance. Incorporation of health and robustness characteristics into breeding programmes could result in improved nutrient use efficiency within livestock systems.

Mechanism of action: Livestock farmers generally aim to improve their stock as a matter of course, however, there is still considerable scope for improvement particularly in the beef and sheep sectors.

Uptake of the ‘best’ genetics is generally good in the poultry, dairy and pig industries, largely through highly integrated breeding and rearing mechanisms used in poultry (meat and egg) production, and the use of artificial insemination (AI) in the dairy and (increasingly) in the pig industry. There is still much scope for health and fertility traits to be included along with yield related traits; this could potentially improve the efficiency of livestock production.

Reduced residual feed intake (food consumption in excess of that required for production) is heritable and breeding programmes that incorporate this trait could result in a permanent reduction in CH_4 emissions. Individual ruminants can have innately reduced CH_4 outputs, possibly associated with rumen protozoal populations, and may be of use in breeding programmes. Breeding for lower residual feed intake in beef cattle and restoring dairy cow fertility levels to 1995 levels could reduce annual methane emissions over a 25 year period by between 10-25% at the farm scale. Increasing the longevity of cows will decrease CH_4 emissions and increase lifetime N use efficiency.

Potential for applying the method: The method is applicable to all livestock systems, but the greatest gains are expected in the beef and sheep sectors.

Practicality: The use of AI on dairy and pig farms mean that new genetics can be introduced very easily to herds. The use of AI in sheep flocks is likely to increase in the future and will enable more rapid development of genetics, as has occurred with dairy cows and pigs.

Likely uptake: Moderate-high, it will take time for widespread adoption in the beef and sheep sectors.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs based on a 10% reduction in feed inputs for the same livestock productivity.
Annual	-7,000	-8,500	-4,500	-2,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O losses and NH_3 emissions would be reduced by up to 10% (from manure management).

P: Losses would be reduced by up to 10% (from manure management).

Methane: Losses could potentially be reduced by up to 10%.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Alford, A. R., R. S. Hegarty, P. F. Parnell, O. J. Cacho, R. M. Herd, and G. R. Griffith. (2006). The impact of breeding to reduce residual feed intake on enteric methane emissions from the Australian beef industry. *Australian Journal of Experimental Agriculture*, 46, 813-820.
Del Prado, A. and Scholefield, D. (2008). Use of SIMSDAIRY modelling framework system to compare the scope on the sustainability of a dairy farm of animal and plant genetic-based improvements with management-based changes. *Journal of Agricultural Science*, 146, 1-17.
Garnsworthy, P.C. (2004). The environmental impact of fertility in dairy cows: A modelling approach to predict methane and ammonia emissions. *Animal Feed Science and Technology*, 112, 211-223.
Goopy, J.P., Hegarty, R.S. and Dobos, R.C. (2006). The persistence over time of divergent methane production in lot fed cattle. *International Congress Series*, 1293, 111-114.
Defra project AC0204 - A study of the scope for the application of research in animal genomics and breeding to reduce nitrogen and methane emissions from livestock based food chains.
Defra project IS0213 - Longevity and lifetime efficiency of dairy cows.
Defra project LK0645 - Endocrine management of bovine infertility (EMBI).
Defra project LK0657 - Identifying and characterising robust dairy cows.
Defra project AC0206 - A review of research of identify best practice for reducing greenhouse gas emissions from agriculture and land management.

Method 20 – Use plants with improved nitrogen use efficiency

Direction of change for target pollutants on cropped land.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	~	~	~	~	↓	↓	~	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	✓	✓	×	×	×	✓

Description: Develop new plant varieties with improved genetic traits for the capture of soil N.

Rationale: During the growing period, the efficiency of uptake of applied manufactured fertiliser N typically ranges between 55 and 70%, according to site conditions, the amount of soil N and the inherent physiology of the plant. If the plant can be rendered more competitive for soil N, reduced emissions of N to water and air would be expected. Improving N use efficiency of plants could potentially therefore:

- Reduce fertiliser N additions to agriculture.
- Improve nutritional characteristics of new forage plant varieties (e.g. improved amino acid profile, reduced rumen protein degradation, improve fibre digestibility).
- Improve N efficiency in agriculture.

Mechanism of action: Plants remove more mineral N from the soil and so reduce the amount that can be lost to water and air.

Potential for applying the method: Can be applied (in principle) to all sectors of agricultural crop production, but has most potential for arable crops.

Practicality: Depends on existence of high N use efficiency plants, with seed at cost-effective prices (and no accompanying management or food quality disbenefits).

Likely uptake: Depends on the increase in cost *vs*. the reduction in crop N requirement. If this ratio is positive, then uptake is likely to be high.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costings assume a 10% reduction in N inputs to arable crops (no account has been taken of possible associated yield benefits).
Annual	-200	-100	-900	-2,500	-3,000	-250	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions, and NH_3 emissions would be reduced by up to 10%.

Other pollutants: CO_2 emissions would be reduced by a small amount as a result lower fertiliser N use (and production). Impacts on other pollutants are likely to be minimal.

Key references:

MAFF (2000). *Fertiliser Recommendations for Agricultural and Horticultural Crops*. RB209. Seventh Edition, The Stationery Office, Norwich.

Defra project OC9412 - Genetic manipulation of the nitrogen efficiency of wheat.

Defra project LK0979 - Breeding oilseed rape with a low requirement for nitrogen fertiliser.

Defra project LK0959 - Genetic reduction of energy use and emissions of nitrogen in cereal production, GREEN grain.

Method 21 – Fertiliser spreader calibration

Direction of change for target pollutants on the area where fertilisers are applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	~	~	~	~	~	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Improve the accuracy and spread pattern of fertiliser spreaders.
Rationale: Inaccurate fertiliser spreading (i.e. poor spread patterns) result in the under-application of fertiliser on some areas and over-application on other areas. Under-application of N fertiliser results in reduced yields and over-application can also result in reduced yields (through lodging) and increased NO_3 leaching losses.
Mechanism of action: Tray tests are used to determine the coefficient of variation (CV) and accuracy of a fertiliser spreader. A low CV (less than 10%) ensures that fertiliser is spread evenly and all parts of the field receive the recommended rate. This optimises the uptake of soil and fertiliser nutrients, and reduces the amount of residual (autumn) mineral N available for leaching over-winter. Fertiliser spreaders should be checked at least annually and, ideally, whenever the fertiliser type is changed.
Potential for applying the method: The method is applicable to all farm types where manufactured fertiliser is used.
Practicality: The method is easily applied, with qualified testers available throughout the country.
Likely uptake: Moderate -high. A low cost method which will improve crop growth, as well as reducing diffuse pollution. The method is encouraged under crop assurance schemes and under NVZ Action Programme rules.
Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on contractor rates (no account is taken of any associated yield improvements).
Annual	150	150	100	150	200	200	50	

Effectiveness:
N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 5% and associated direct and indirect N_2O emissions.
Other pollutants: Impacts on other pollutants are likely to be minimal.
Key references:

Chaney, K. (1990). Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. *J. Agric. Sci. Camb.,* 114, 171-176.
Defra/EA (2008). *Guidelines for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.
Shepherd, M.A. and Sylvester-Bradley, R. (1996). Effect of nitrogen fertiliser applied to winter oilseed rape on soil mineral nitrogen after harvest and on the response of a succeeding crop of winter wheat to nitrogen. *Journal of Agricultural Science,* 126, 63-74.
WAgriCo - http://www.wagrico.org.uk

Method 22 – Use a fertiliser recommendation system

Direction of change for target pollutants on the area where fertiliser is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	~	~	↓	↓	~	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Use a recognised fertiliser recommendation system (e.g. RB209, PLANET and other supplementary guidance) to plan *manufactured fertiliser applications* to all crops; do not exceed recommended rates. Time fertiliser applications to minimise the risk of nutrient losses (e.g. avoid autumn N use and manage early spring applications to drained soils). Take full account of manure nutrient supply when planning manufactured fertiliser applications. Use a professional FACTS (Fertiliser Advisers Certification and Training Scheme) qualified adviser.

Rationale: Fertiliser recommendation systems take account of the following factors: soil nutrient supply (based on soil analysis), winter rainfall, previous cropping and soil type, crop nutrient requirements for a given soil and climate, crop requirement for nutrients at various growth stages, the amount of nutrients supplied to the crop by added organic manures and by previous manure applications, soil pH and the need for lime. Use of a fertiliser recommendation system will reduce the risk of applying more nutrients than the crop needs and will minimise the risks of causing diffuse water and air pollution.

Mechanism of action: A good fertiliser recommendation system ensures that the necessary quantities of nutrients are available when required for uptake by the crop. Nutrients are only applied when the supply of nutrients from all other sources is insufficient to meet crop requirements. As a result, the amount of excess nutrients in the soil is reduced to a minimum. Use of a recommendation system should also ensure that the soil is in a sufficiently fertile state to maximise the efficient use of nutrients already in the soil, or supplied from other sources such as fertilisers/organic manures. Maintaining an appropriate balance between different nutrients (i.e. NPK) is also important to maximise the efficient uptake of all nutrients and reduce environmental losses to a minimum.

Potential for applying the method: Fertiliser recommendation systems can be used in all farming systems, but are particularly useful in high output grassland, arable and horticultural systems. The method would have less impact in extensive grassland systems, as manufactured fertiliser addition rates are low/moderate.

Practicability: The method would require additional investment in education and guidance on some farms.

Likely uptake: Moderate/high. As long as fertiliser prices are ‘high’ relative to the value of the crop farmers will want to optimise nutrient inputs. Improvements are most likely when organic manures are used.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on a 5% reduction in fertiliser use.
Annual	-2,200	-1,400	-2,000	-3,100	-3,200	-3,800	-400	

Effectiveness

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 5% and associated direct and indirect N_2O emissions, and NH_3 emissions.

P: P losses would be reduced by up to 5% (from applied fertilisers).

Other pollutants: CO_2 emissions would be reduced by a small amount as a result of lower fertiliser use (and production). Impacts on other pollutants are likely to be minimal

Key references:

Defra (2010). *Fertiliser Manual (RB209)*, 8th Edition. The Stationery Office, Norwich. ISBN 978-0-11-243286-9.

Chaney, K. (1990). Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. *J. Agric. Sci. Camb.,* 114, 171-176.

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Lord, E.I., Shepherd, M.A., Silgram, M, Goodlass, G., Gooday, R, Anthony, S.G., Davison, P. and Hodgkinson, R. (2007). *Investigating the Effectiveness of NVZ Action Programme Measures: Development of a Strategy for England*. Report for Defra Project NIT18.

MAFF (2000). *Fertiliser Recommendations for Agricultural and Horticultural Crops (RB209).* 7th edition. The Stationery Office, Norwich.

Shepherd, M.A. and Sylvester-Bradley, R. (1996). Effect of nitrogen fertiliser applied to winter oilseed rape on soil mineral nitrogen after harvest and on the response of a succeeding crop of winter wheat to nitrogen. *Journal of Agricultural Science,* 126, 63-74.

Withers, P. J. A., Clay, S. D. and Breeze, V. G. (2001). Phosphorus transfer in runoff following application of fertilizer, manure and sewage sludge. *Journal of Environmental Quality*, 30, 180-188.

Withers, P. J. A., Ulen, B., Stamm, C. and Bechmann, M. (2003). Incidental phosphorus loss – is it significant and can it be predicted? *Journal of Soil Science and Plant Nutrition*, 166, 459-468.

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Method 23 – Integrate fertiliser and manure nutrient supply

Direction of change for target pollutants on the area where manure and fertilisers are applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	~	~	↓	↓	~	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✗	✗	✓

Description: Use a recognised fertiliser recommendation system (e.g. RB209, PLANET, MANNER-*NPK* and other supplementary guidance) to make *full allowance of the nutrients applied in organic manures* and reduce manufactured fertiliser inputs accordingly. Use laboratory analysis to gain a better understanding of manure nutrient contents and supply. Use a professional FACTS (Fertiliser Advisers Certification and Training Scheme) qualified adviser.

Rationale: Recommendation systems should be used to provide a robust estimate of the amount of nutrients supplied by organic manure applications (e.g. RB209, PLANET, MANNER-*NPK*). This information can then be used to determine the amount and timing of additional manufactured fertilisers needed by the crop. Fertiliser use statistics suggest that, in many cases, this will result in a reduction in fertiliser inputs (particularly on arable and maize crops) compared with current practice and a concomitant reduction in diffuse nutrient pollution. The British Survey of Fertiliser Practice indicates that farmers *do not always* make full allowance for the nutrients supplied by organic manures when calculating fertiliser application rates.

Mechanism of action: Manufactured fertiliser application rates are reduced to no more than required for optimum economic production levels and to maintain adequate nutrient levels in the soil. Where soil P and K levels are satisfactory (i.e. ADAS Index 2), manure inputs will usually meet the needs of the next crop grown. Indeed, repeated manure applications can lead to a build-up of soil P reserves.

Potential for applying the method: Most applicable to arable and high output grassland systems (including maize). The method is effective wherever manufactured fertilisers are used to ‘top-up’ the nutrients supplied by organic manures.

Practicability: The method could be easily implemented *via* advice, education and guidance. Particular guidance is required with manure (and soil) sampling, the use of on-farm slurry analysis methods, and the interpretation of results.

Likely uptake: Moderate-high, mainly as a result of the increasing cost of manufactured fertilisers, meaning the nutrient inputs from manures are more likely to be taken into account in order to reduce costs.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on a 10-15% reduction in fertiliser use where manures applied.
Annual	-4,500	-2,900	-4,100	-6,300	-6,500	-7,600	-800	

Effectiveness:

N: NO$_3$ (plus ammonium and nitrite) leaching losses would be reduced by up to 10% and associated direct and indirect N$_2$O emissions, and NH$_3$ emissions. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

P: P losses would be reduced by up to 10% (from applied fertiliser).

Other Pollutants: CO$_2$ emissions would be reduced by a small amount as a result of lower fertiliser use (and production). Impacts on other pollutants are likely to be minimal.

Key references:

Chambers, B.J., Lord, E.I., Nicholson, F.A. and Smith, K.A. (1999). Predicting nitrogen availability and losses following application of organic manures to arable land: MANNER. *Soil Use and Management*, 15, 137-143.

Chambers, B.J., Smith, K.A. and Pain, B.F. (2000). Strategies to encourage better use of nitrogen in animal manures. *Soil Use and Management, Tackling Nitrate from Agriculture*, 16, 157-161.

Chaney, K. (1990). Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. *J. Agric. Sci. Camb.* 114, 171-176.

Defra (2010). *Fertiliser Manual (RB209),* 8th Edition. The Stationery Office, Norwich. ISBN 978-0-11-243286-9.

Haygarth, P. M. and Jarvis, S. C. (1999). Transfer of phosphorus from agricultural soils. *Advances in Agronomy*, 66, 195-249.

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Withers, P. J. A., Clay, S. D. and Breeze, V. G. (2001). Phosphorus transfer in runoff following application of fertilizer, manure and sewage sludge. *Journal of Environmental Quality,* 30, 180-188.

Withers, P. J. A., Ulen, B., Stamm, C. and Bechmann, M. (2003). Incidental phosphorus loss – is it significant and can it be predicted? *Journal of Soil Science and Plant Nutrition,* 166, 459-468.

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Method 24 – Reduce manufactured fertiliser application rates

Direction of change for target pollutants on the area where fertiliser is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	~	~	↓	↓	~	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Reduce the amount of manufactured N and P fertiliser applied to crops *below the economic optimum rate*.

Rationale: Limiting the amount of N fertiliser applied to crops will reduce the quantity of residual NO_3 in the soil after harvest. Limiting P fertiliser will in the short-term reduce the amount of soluble P lost and in the longer-term will reduce the amount at risk of loss as particulate P.

Mechanism of action: The amount of fertiliser applied is reduced at source. There will be a reduction in the amount of residual soil NO_3 available for leaching in the autumn, however, there will be no effect on the amount of NO_3 mineralised from soil organic matter that will also be available for leaching over-winter. Limiting P fertiliser applications in any one year will reduce the amount of soluble P at risk of loss in surface runoff or drainflow and in the longer-term (where soil P reserves have run down) there will be a reduction in both soluble and particulate P losses.

Potential for applying the method: The method is applicable to all farming systems where fertiliser is used.

Practicability: The method would have a significant impact on crop yields (other than legumes). For example, a 20% reduction in fertiliser N use (below the economic optimum rate) would typically result in a 2-10% reduction in crop yields. The impact of reducing fertiliser P use would be greatest for responsive crops (e.g. potatoes and some vegetable crops). It is important that any reduction in fertiliser use should take account of the interactions between nutrients and not create an imbalance in the soil. A shortage of one nutrient may limit uptake of another and potentially increase losses of the second nutrient.

Likely uptake: Low, due to impact on yields and farm income. Small reductions in yield can have a (disproportionately) large effect on the economic viability of a farm business. Financial incentives would be required to encourage uptake.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Gross margin calculations take into account crop yield and 20% nutrient use reductions.
Annual	10,200	1,200	1,100	6,000	13,000	54,000	14,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 10% (from a 20% reduction in N fertiliser rates) and associated direct and indirect N_2O emissions, and NH_3 emissions.

P: Soluble P losses would be reduced by up to 10% (from a 20% reduction in P fertiliser rates) plus longer-term reductions through reduced soil P status.

Other pollutants: CO_2 emissions would be reduced by a small amount as a result of lower fertiliser use (and production). Impacts on other pollutants are likely to be minimal.

Key references:

Chambers. B.J. and Chalmers, A.G. (1994). Effects of combinable crop output values on the economics of fertiliser use. *Aspects of Applied Biology, Arable Farming under CAP Reform*, 40, 377-386.

Chaney, K. (1990). Effect of nitrogen fertilizer rate on soil nitrate nitrogen content after harvesting winter wheat. *J. Agric. Sci. Camb.* 114, 171-176.

Haygarth, P. M. and Jarvis, S. C. (1999). Transfer of phosphorus from agricultural soils. *Advances in Agronomy,* 66, 195-249.

MAFF (2000). *Fertiliser Recommendations for Agricultural and Horticultural Crop*s (RB209). 7th edition. The Stationery Office, Norwich.

Shepherd, M.A. and Sylvester-Bradley, R. (1996). Effect of nitrogen fertiliser applied to winter oilseed rape on soil mineral nitrogen after harvest and on the response of a succeeding crop of winter wheat to nitrogen. *Journal of Agricultural Science,* 126, 63-74.

Sylvester-Bradley, R. and Chambers, B.J. (1992). The implications of restricting use of fertiliser nitrogen for the productivity of arable crops, there profitability and potential pollution by nitrate. *Aspects of Applied Biology, Nitrate and Farming Systems*, 85-94.

Withers, P. J. A., Clay, S. D. and Breeze, V. G. (2001). Phosphorus transfer in runoff following application of fertilizer, manure and sewage sludge. *Journal of Environmental Quality,* 30, 180-188.

Withers, P. J. A., Ulen, B., Stamm, C. and Bechmann, M. (2003). Incidental phosphorus loss – is it significant and can it be predicted? *Journal of Soil Science and Plant Nutrition*, 166, 459-468.

Defra project NT1830 - Effects of crop yield: management and N fertiliser rate on nitrate leaching, yield and soil N status.

Method 25 – Do not apply manufactured fertiliser to high-risk areas

Direction of change for target pollutants on the area where fertiliser is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	↓	~	~	~	↓	↓	~	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✗	✗	✓

Description: Do not apply manufactured fertiliser at any time to field areas where there are direct flow paths to watercourses. For example, areas with a dense network of open drains, wet depressions (flushes) draining to a nearby watercourse, or areas close to road culverts/ditches.

Rationale: The risk of N and P pollution is reduced by not applying fertiliser at any time to areas where it could easily be transferred to a watercourse.

Mechanism of action: Avoiding fertiliser spreading to hydrologically well connected areas helps prevent the transfer of pollutants to water.

Potential for applying the method: This method is potentially applicable to all farming systems, but is probably most applicable to the grassland sector, where open drains and waterlogged areas are most common. It is also applicable to all fields with ditches and areas close to road culverts.

Practicability: It is an easy option to implement, although (some) farmers may still want to apply fertiliser to grassland that contains areas prone to waterlogging or with a dense network of open drains.

Likely uptake: Moderate to high. A no fertiliser spreading buffer of 2 m from surface waters is mandatory in Nitrate Vulnerable Zones.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on loss of gross margin on 1% of farm area.
Annual	100	20	20	50	1,000	3,600	950	

Effectiveness:

N: Nitrate (plus ammonium and nitrite) leaching losses would be reduced by a small amount (up to 2%) and there would be associated small reductions in direct and indirect N_2O emissions, and NH_3 emissions.

P: Soluble P losses would be reduced by up to 10%, as hydrologically well connected areas can make a large contribution to P losses.

Other pollutants: CO_2 emissions would be reduced by a small amount as a result of lower fertiliser use (and production). Impacts on other pollutants are likely to be minimal.

Key references:

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i

Haygarth, P.M., Heathwaite, A.L., Jarvis, S.C. and Harrod, T.R. (2000). Hydrological factors for phosphorus transfer from agricultural soils. *Advances in Agronomy*, 69, 153-178.

Haygarth, P. M. and Jarvis, S. C. (1999). Transfer of phosphorus from agricultural soils. *Advances in Agronomy*, 66, 195-249.

Withers, P. J. A., Clay, S. D. and Breeze, V. G. (2001). Phosphorus transfer in runoff following application of fertilizer, manure and sewage sludge. *Journal of Environmental Quality*, 30, 180-188.

Withers, P. J. A., Ulen, B., Stamm, C. and Bechmann, M. (2003). Incidental phosphorus loss – is it significant and can it be predicted? *Journal of Soil Science and Plant Nutrition*, 166, 459-468.

Method 26 – Avoid spreading manufactured fertiliser to fields at high-risk times

Direction of change for target pollutants on the area where fertiliser is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	↓	~	~	~	↓	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✗	✗	✓

Description:

- Do not spread manufactured fertiliser at times when there is a high-risk of surface runoff or rapid movement to field drains i.e. when soils are ‘wet’.
- Do not spread N fertiliser between September and February when there is little or no crop uptake and there is a high-risk of NO_3 leaching loss; unless there is a specific crop requirement during this period.

Rationale: Fertiliser timing affects the potential for mobilisation of nutrients from land to water. Avoiding spreading fertiliser to fields at high-risk times reduces the availability of N and P for loss in surface runoff or drainflow.

Mechanism of action: Surface runoff is most likely to occur when rain falls on sloping ground, when soils are ‘wet’, frozen or snow covered. The rapid preferential flow, through the soil, of N and P from applied fertilisers is most likely to occur from (drained) soils when they are ‘wet’ and rainfall follows soon after application. This method aims to prevent nutrients being added at times when there is potential for rapid transfer to water. Avoiding N fertiliser application in the autumn/winter reduces the amount of NO_3 available for leaching by over-winter rainfall.

Potential for applying the method: The method is potentially applicable to all farming systems, which use fertilisers. Closed spreading periods for manufactured fertiliser N already exist in NVZs, unless a specific crop requirement can be justified.

Practicability: The method would be acceptable to most farmers, although restrictions on the timing of manufactured N (and P) applications to ‘wet’ soils in spring may cause practical difficulties for some farmers. The adoption of this method would require a degree of education and advisory activity to ‘persuade’ farmers that the spreading of fertiliser at high-risk times (e.g. when soils are ‘wet’ and surface runoff or drainflow losses may occur) should not be undertaken.

Likely uptake: Moderate to high. However, farmers may be reluctant not to apply fertiliser N to ‘wet’ soils in spring to support early season crop growth.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on small crop yield penalty through delayed spring fertiliser application.
Annual	100	30	70	300	800	850	100	

Effectiveness:

N: Nitrate (plus ammonium and nitrite) leaching losses would be reduced by a small amount (up to 5%) and direct and indirect N_2O emissions, and NH_3 emissions.

P: Soluble P losses would be reduced by up to 10%, as hydrologically well connected areas can make a large contribution to P losses.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Chalmers, A. and Froment, M. (1992). The effect of seedbed nitrogen and straw incorporation for winter oilseed rape on leaching losses of nitrate in sandy and chalk soils. *Aspects of Applied Biology*, 30, 275-278.

Hart, M., Quin, B. and Nguyen, M. (2004) Phosphorus runoff from agricultural land and direct fertiliser effects: a review. *Journal of Environmental Quality*, 33, 1954-1972.

Lord, E.I. and Mitchell, R.D. (1998). Effect of nitrogen inputs to cereals on nitrate leaching from sandy soils. *Soil Use and Management*, 14, 78-83.

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Method 27 – Use manufactured fertiliser placement technologies

Direction of change for target pollutants where fertiliser placement is used.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	↓	~	~	~	↓*	↓	~	↑

* Where urea fertiliser placed.

Farm typologies applicable:

Dairy*	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✗	✗	✗*	✗*	✗	✓	✗	✗	✗	✓

* Fertiliser placement for maize is part of farm ‘baseline’ i.e. is normal practice.

Description: Place nutrients close to germinating or established crops to increase fertiliser N and/or P recovery.

Rationale: Placement of nutrients close to plant seeds and roots increases nutrient uptake efficiency.

Mechanism of action: Fertiliser placement can be particularly useful in low P status soils to increase uptake efficiency and can also enable reductions in fertiliser application rates through improved nutrient recovery (without any impact on yield). Placement also reduces exposure of fertiliser at the soil surface, thereby reducing the potential for incidental losses in surface runoff from sloping ground.

Potential for applying the measure: Fertiliser placement technology is applicable to a wide range of vegetable and potato (and maize) crops; where the method is already widely used.

Practicality: Fertiliser placement technology is readily available and tailor-made liquid fertiliser products are made to meet high value crop nutrient requirements.

Likely uptake: Moderate to high. Uptake of fertiliser placement technology may increase further as manufactured fertiliser prices continue to rise over the longer-term. Due to the initial capital expenditure required, it is most likely to be taken up by large arable/vegetable businesses or where contractors are used.

Cost:

Total *cost* for farm system (£/farm)	Comb/ Roots	Hort	Costs based on additional operational inputs (no change in fertiliser inputs).
Annual	50	20	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small (up to 2%) amount and direct and indirect N_2O emissions, and NH_3 emissions (through reduced volatilisation losses from urea).

P: Soluble P losses would be reduced by up to 5% (through reduced surface runoff risks).

Other pollutants: CO_2 emissions would be increased by a small amount through the use of placement technology. Impact on other pollutants are likely to be minimal.

Key references:

Withers, P. J. A., Ulen, B., Stamm, C. and Bechmann, M. (2003). Incidental phosphorus loss – is it significant and can it be predicted? *Journal of Soil Science and Plant Nutrition*, 166, 459-468.
Defra project NT1209 - Improving the efficiency of nitrogen fertiliser use by fertiliser placement.

Method 28 – Use nitrification inhibitors

Direction of change for target pollutants where inhibitors used.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
(↓)	(↑)	(↑)	~	~	~	~	~	(↑)	(↓↓)	~	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✗	✗	✓

Description: Addition of nitrification inhibitors (NIs) to applied manufactured N fertilisers, organic manures and to grazed pastures.

Rationale: NIs are chemicals that slow the rate of conversion of NH_4 to NO_3, so that NO_3 is formed at a rate that is in better 'synchrony' with crop demand (i.e. slow release) and will thereby increase N use efficiency and reduce N_2O emissions and NO_3 leaching.

Mechanism of action: NI compounds such as dicyandiamide (DCD), nitrapyrin and 3,4-dimethylpyrazole phosphate (DMPP) have been shown to be effective in reducing N_2O emissions and NO_3 leaching losses from fertiliser/animal manure additions and grazed pastures, and to improve crop N use efficiency.

Potential for applying the method: NIs can be included in manufactured N fertiliser formulations, added to manures, applied to grazed pastures and to animals (via slow release boluses). Work in New Zealand has shown that NO_3 leaching losses can be reduced by up to 35%. Similarly, research in New Zealand has shown that NIs can reduce N_2O emissions by 30-70% under field conditions. However, in New Zealand, most grazing paddocks are on free draining soils and the growing season is much longer than in the UK.

Practicability: NIs can be included in fertiliser/manure applications and applied to grazed pastures.

Likely uptake: Low-moderate. NIs are relatively expensive, which is likely to reduce uptake by farmers. However, reductions in manufactured fertiliser N requirements, through reduced N losses/additions, may offset this cost.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Based on use cost of £20/ha.
Annual	2,000	1,300	1,800	1,900	3,200	3,000	300	

Effectiveness:

N: NO_3 leaching loss reductions of up to 35% (and associated indirect N_2O emissions) and direct N_2O emission reduction of up to 70% have been measured. However, NH_3 emissions to air and ammonium/nitrite losses to water may be increased by a small amount.

Note: Ongoing Defra-funded research (project AC0113) is assessing the potential of NIs to reduce N_2O/NO_3 emissions and the potential for 'pollution swapping' with other N forms (e.g. NH_3 emissions to air).

Other pollutants: CO_2 emissions would be increased by a small amount through NI use (and production). Impacts on other pollutants are likely to be minimal.

Key references:

Chambers, B.J., Smith, K.A. and Pain, B.F. (2000). Strategies to encourage better use of nitrogen in animal manures. *Soil Use and Management, Tackling Nitrate from Agriculture*, 16, 157-161.

Di, H.J., Cameron, K.C. and Sherlock, R.R. (2007). Comparison of the effectiveness of a nitrification inhibitor, dicyandiamide, in reducing nitrous oxide emissions in four different soils under different climatic and management conditions. *Soil Use and Management,* 23, 1-9.

Dittert, K., R. Bol, R. King, D. Chadwick, and D. Hatch. (2001). Use of a novel nitrification inhibitor to reduce nitrous oxide emission from N-15 labelled dairy slurry injected into soil. *Rapid Communications in Mass Spectrometry*, 15, 1291-1296.

Hatch, D., H. Trindade, L. Cardenas, J. Carneiro, J. Hawkins, D. Scholefield, and D. Chadwick. (2005). Laboratory study of the effects of two nitrification inhibitors on greenhouse gas emissions from a slurry treated arable soil: impact of diurnal temperature cycle. *Biology and Fertility of Soils*, 41, 225-232.

Moir, J.L., Cameron, K.C. and Di, H.J. (2007). Effects of the nitrification inhibitor dicyandiamide on soil mineral N, pasture yield, nutrient uptake and pasture quality in a grazed pasture system. *Soil Use and Management,* 23, 111-120.

Method 29 – Replace urea fertiliser with another nitrogen form (e.g. ammonium nitrate)

Direction of change for target pollutants on the area where manufactured urea fertiliser applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↓	↓	~	~	~	~	~	↓↓↓	(↑)	~	~

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Replace urea or urea-based (e.g. urea ammonium nitrate - UAN) fertiliser, with another form of manufactured fertiliser N (*e.g.* ammonium nitrate - AN).

Rationale: Urea and urea-based fertilisers are associated with higher NH_3 emissions (typically around 20% of total N applied for urea and 10% for UAN) than other forms of manufactured fertiliser N.

Mechanism of action: Following land application, urea will undergo hydrolysis to form ammonium carbonate (the rate depends on temperature, moisture and presence of the urease enzyme). This process greatly increases pH around the urea fertiliser and leads to an enhanced potential for NH_3 emissions. This is in contrast to fertiliser forms such as ammonium nitrate, where NH_4 (and dissolved NH_3) will be in equilibrium at a much lower pH, greatly reducing the potential for NH_3 emissions.

Potential for applying the method: All currently used urea and urea-based fertilisers could be replaced with AN or other form of N (*e.g.* AN, ammonium phosphate, ammonium sulphate).

Practicability: There should be no practical reasons why urea and urea-based fertilisers cannot be replaced with another fertiliser N type, although such a method may not be enforceable (under World Trade Agreements). Lower cost per unit of N is the main reason for urea use.

Likely uptake: Low, the main reason urea is used is due to the lower cost per unit of N. Farmers are often ‘unaware’, or don’t recognise, the potential for elevated NH_3 emissions and associated potential yield losses from urea use.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Cost savings based on ammonium nitrate being more cost-effective than urea (when applied at the same rate).
Annual	-500	-300	-500	-200	-800	-900	-100	

Effectiveness:

N: NO_3 leaching losses are likely to be increased by a small amount (up to 5%) and associated indirect N_2O emissions, and direct N_2O emissions (*c.*20%) as more mineral N is retained in the soil through reduced NH_3 emissions to air (*c.*20% of total N applied). Ammonium and nitrite losses to water maybe decreased by a small amount. *Overall* crop N use efficiency would be increased.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Defra (2010). *Fertiliser Manual (RB209)*. 8th Edition. The Stationery Office, Norwich. ISBN 978-0-11-243286-9.

Chambers, B.J. and Dampney, P. (2009). Nitrogen efficiency and ammonia emissions from urea-based and ammonium nitrate fertilisers. *International Fertiliser Society Proceedings*, No. 657, 20pp.

Harrison, R. and Webb, J. (2001). A review of the effect of N fertilizer type on gaseous emissions. *Advances in Agronomy,* 73, 65-108.

Misselbrook, T.H., Sutton, M.A. and Scholefield, D. (2004). A simple process-based model for estimating ammonia emissions from agricultural land after fertilizer applications. *Soil Use and Management,* 20, 365-372.

Defra project NT2605. The behaviour of some different fertiliser N materials – main experiments.

Method 30 – Incorporate a urease inhibitor with urea fertiliser

Direction of change for target pollutants on the area where manufactured urea fertiliser is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓	↑	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description Incorporate a urease inhibitor into solid urea, liquid urea/ammonium nitrate (UAN) solutions etc.

Rationale: Urease inhibitors delay the conversion of urea to ammonium carbonate; this delay allows urea fertiliser to be solubilised and ‘washed’ into the soil and also reduces the pH rise around the urea fertiliser.

Mechanism of action: Urease inhibitors, such as N-(n-butyl)-thiophosphoric triamide (nBTPT) or other similar products, slow the hydrolysis of urea by inhibiting the urease enzyme in the soil. Slowing urea hydrolysis allows more time for urea to be ‘washed’ into the soil and reduces the soil pH increase in close proximity to the applied urea and thereby the potential for NH_3 emissions.

Potential for applying the method: A urease inhibitor could potentially be incorporated into solid urea and UAN solutions. nBTPT has been shown in UK research to reduce NH_3 emissions from solid urea by a mean of 70% and from liquid UAN by a mean of 40%.

Practicability: Other than costs and product registration issues there are no major barriers to use.

Likely uptake: Low-moderate. The main issue would be justifying the cost-benefit of use, as many farmers are ‘unaware’/don’t ‘recognise’ the potential for elevated NH_3 emissions and associated yield losses from urea use.

Cost: No net cost; as ammonia emission reductions are likely to be ‘balanced’ by the cost of the urease inhibitor.

Effectiveness:

N: NH_3 emissions would be reduced by around 70% from solid urea and around 40% for UAN. There would be associated small increases in NO_3 (ammonium and nitrite) leaching losses to water and direct and indirect N_2O emissions to air; as more mineral N is retained in the soil. Crop N use efficiency would also increase.

Other pollutants: Impacts on other pollution are likely to be minimal.

Key references:

Chambers, B.J. and Dampney, P. (2009). Nitrogen efficiency and ammonia emissions from urea-based and ammonium nitrate fertilisers. *International Fertiliser Society Proceedings* No. 657, 20pp.

Defra project NT2605. The behaviour of some different fertiliser N materials – main experiments.

Method 31 – Use clover in place of fertiliser nitrogen

Direction of change for target pollutants on the area of grassland.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	~	~	~	~	↓↓	↓↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✗	✗	✗	✗

Description: Use clover in place of fertiliser N to fix nitrogen from the air, resulting in lower manufactured fertiliser N use.
Rationale: By using clover in a grass sward the need for additional manufactured N fertiliser is reduced.
Mechanism of action: *Rhizobium trifolii* present in root nodules of the host clover plant fix di-nitrogen gas, which is then nitrified within the plant system. However, fixation by legumes can be repressed through the application of fertiliser N.
Potential for applying the method: This method is applicable to most grassland systems, but may entail a reduction in stocking rates where high rates of manufactured N fertiliser have previously been used.
Practicality: The method would be reasonably simple to implement on farms looking to maintain (slightly reduce) stock numbers on low-moderate output systems, and should reduce costs by replacing manufactured N fertiliser with biologically fixed N. However, for higher output systems careful management would be need to ensure that grassland production was not compromised.
Likely uptake: Moderate; with little uptake on high N fertiliser systems.
Cost: No net cost; we have assumed that the cost of establishing clover was offset by savings in fertiliser N use (*c*.50%) on low-moderate output systems.
Effectiveness:
N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 20%. There would be associated reduction in direct (up to 50%) and indirect (up to 20%) N_2O emissions, and NH_3 emissions (*c*.50%).
Other pollutants: Impacts on other pollutants are likely to be minimal.
Key references:

Cuttle, S.P. and James, A.R. (1995). Leaching of lime and fertilisers from a reseeded upland pasture on a stagnogley soil in mid-Wales. *Agricultural Water Management,* 28, 95-112.
Cuttle, S.P. and Scholefield, D. (1995). Management options to limit nitrate leaching from grassland. *Journal of Contaminant Hydrology,* 20, 299-312.
Defra project NT1602 - Understanding the grassland nitrogen cycle in order to improve fertiliser recommendations (previously NT0601).
Defra project NT1806 - To develop a predictive capacity for N loss from grassland.
Defra project NT1825 - Nitrate leaching in sustainable livestock LINK project (LK0613).
Defra project NT2511 - Cost curve of nitrate mitigation options.

Method 32 – Do not apply P fertiliser to high P index soils

Direction of change for target pollutants on high P Index soils.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	↓	↓↓	~	~	~	~	~	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Do not apply manufactured P fertiliser to soils that have an ADAS soil P Index of 4 or above.

Rationale: The amount of P lost via soil erosion or leaching depends on the soil P status. Losses in solution increase rapidly once soil P reserves reach elevated levels (e.g. ADAS Soil P index 4 or above). Losses can be minimised by maintaining soil P levels at Index 2 or by allowing the P content of high P index soils to run-down overtime.

Mechanism of action: If manufactured P fertiliser is not applied and the P content of high P index soils is allowed to decline, the amount of P lost with eroded soil particles and in solution will be reduced. Phosphorus is adsorbed onto soil particles and is lost when sediment is eroded from fields (in surface runoff/drainflow); the higher soil P reserves the greater the amount of P lost. However, the run-down of high soil P reserves is a gradual process and full benefits will only be achieved in the longer-term (>10 years). Also, the amount of P lost in soil solution is greater from high P index soils.

Potential for applying the method: The method is potentially applicable to all farming systems, but would most likely be applied to high output grassland, arable and horticultural farms.

Practicability: The method could easily be implemented via advice, education and guidance i.e. soil sampling, analysis and interpretation of soil P Index levels. There may be resistance to adopting the method for those crops (e.g. potatoes/vegetable crops) that are most responsive to P inputs.

Likely uptake: Moderate. ‘High’ P fertiliser prices mean that there is an increasing tendency for farmers to run-down high P status soils (i.e. they are already likely not to be using P fertilisers where they are not needed).

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on fertiliser P input reduction of 10%.
Annual	-500	-350	-500	-750	-750	-900	-100	

Effectiveness:

P: Soluble P losses would be reduced (over the longer-term) by up to 50% and particulate P losses by up to 30% (over the longer-term).

Other pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Haygarth, P.M., Heathwaite, A.L., Jarvis, S.C. and Harrod, T.R. (2000). Hydrological factors for phosphorus transfer from agricultural soils. *Advances in Agronomy*, 69, 153-178.

Haygarth, P. M. and Jarvis, S. C. (1999). Transfer of phosphorus from agricultural soils. *Advances in Agronomy*, 66, 195-249.

Smith, K.A., Chalmers, A.G., Chambers, B.J. and Christie, P. (1998). Organic manure phosphorus accumulation, mobility and management. *Soil Use and Management*, 14, 154-159.

Withers, P. J. A., Clay, S. D. and Breeze, V. G. (2001). Phosphorus transfer in runoff following application of fertilizer, manure and sewage sludge. *Journal of Environmental Quality,* 30, 180-188.

Withers, P. J. A., Ulen, B., Stamm, C. and Bechmann, M. (2003). Incidental phosphorus loss – is it significant and can it be predicted? *Journal of Soil Science and Plant Nutrition,* 166, 459-468.

Method 33 – Reduce dietary N and P intakes

Direction of change for target pollutants on livestock farms.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	~	~	↓	↓	↓*	~

* Where maize included in dairy cow diets.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✓	✓	✓	✗

Description: Adjust the composition of livestock diets to reduce the total intake of N and P per unit of production.

Rationale: Avoiding excess N and P in the diet and/or making dietary N and P more available allows nutrient concentrations in the diet to be reduced, without adversely affecting animal performance. These methodologies reduce the amount of N and P excreted, either directly to fields or *via* handled manures, and thereby minimise additions as sources of diffuse pollution.

Mechanism of action: Farm animals are often fed diets with higher than recommended contents of N and P, as a safeguard against a loss of production, arising from a deficit of these nutrients. However, surplus N and P will not be utilised by the animal and will be excreted. Restricting diets to recommended levels of N and P will limit the amounts excreted.

Nutrient excretion can also be reduced by changing the composition of the diet to increase the proportion of dietary N and P utilised by the animal; for example, by optimising the balance of N to carbohydrate in ruminant diets or by reducing the proportion of rumen-degradable protein. Additionally, in non-ruminants, N excretion can be reduced by increasing the digestibility of the ration. In both ruminants and non-ruminants, feeding a ration that supplies amino acids in the ideal proportions required for protein synthesis will reduce the quantities of ‘surplus’ amino acids that remain un-utilised and contribute to N excretion. Supplementing the diet of pigs and poultry with the enzyme phytase, increases the availability of P in the feed and allows total P contents to be reduced without affecting productivity (this is not applicable to ruminants as rumen microbes produce phytase naturally).

Potential for applying the method: Benefits are likely to be greatest on dairy, pig and poultry units, and least on beef/sheep units that feed a largely forage-based diet. The extent to which these methods can be applied depends on the proportion of farms currently feeding excess N and P, or not already using feed supplements. Opportunities for reducing N and P in ruminant diets are probably limited, as very little is added to beef feeds and recent reductions in dairy diets have removed a significant proportion of any excess; although education is still needed. Precise formulation of diets requires accurate analytical data about the chemical composition of the feedstuffs, which may not be readily available for forages.

For pigs, there is potential and the technical know-how to reduce N inputs, but implementation has been limited (by the lack of economic incentives). There is little scope for further reducing P inputs, which have already been reduced because of economic pressures; phytase enzymes are universally included in pig diets.

For poultry, considerable steps have already been made through the use of whole wheat feeding and synthetic amino acid inclusion in broiler diets; there is limited scope for further reducing the N content of poultry diets, without reducing outputs.

Practicability: Many protein feeds are rich in P and it can be difficult to formulate least-cost rations, with optimum contents of both N and P. Within the dairy sector, there is already a focus on lowering total diet crude protein contents, optimising the protein:energy balance in the rumen and supplying adequate metabolisable protein. Reducing the crude protein content of the diet (to 14%) may be a significant challenge in areas relying on grass silage production for forage. Also, matching performance to requirement has cost, labour and housing implications.

For poultry, there are concerns that reducing nutrient inputs further may have adverse effects on reproductive performance and carcass quality. The scope to use more digestible materials in broiler diets is also limited, as most diets already include feed materials of high digestibility. There is an economic incentive to use phytase, but (presently) this has not been widely adopted by the broiler industry.

For pigs, there is scope to reduce N inputs, but (presently) this has not been widely adopted by the industry.

Likely uptake: Low-moderate in dairy sector. In the pig sector, uptake for P is already high and uptake for N would be higher with stronger economic incentives. In the poultry sector, uptake for N and P is already high, although there is potential to increase phytase use in the broiler industry.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Indoor pigs	Out pigs	Poultry	Costs based on additional feed and management inputs to avoid excess N & P.
Annual	5,900	1,100	1,300	2,500	4,000	6,250	600	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 10% and direct and indirect N_2O emissions, and NH_3 emissions (by up to 10%).

P: Soluble P losses would be reduced by up to 10% and in the longer-term particulate P losses.

Other pollutants: CH_4 emissions would be reduced by a small amount if dairy cow N intake was reduced by maize use in place of grass silage. Impacts on other pollutants are likely to be minimal.

Key references:

Del Prado, A. and D. Scholefield. (2008). Use of SIMSDAIRY modelling framework system to compare the scope on the sustainability of a dairy farm of animal and plant genetic-based improvements with management-based changes. *Journal of Agricultural Science*, 146, 1-17.

Dourmad, J.Y. and Jondreville, C. (2007). Impact of nutrition on nitrogen, phosphorus, Cu and Zn in pig manure on emissions of ammonia and odours. *Livestock Science,* 112, 192-198.

Misselbrook, T. H., Powell, J. M., Broderick, G. A. and Grabber, J. H. (2005). Dietary manipulation in dairy cattle: laboratory experiments to assess the influence on ammonia emissions. *Journal of Dairy Science,* 88, 1765-1777.

Misselbrook, T. H., Chadwick, D. R., Pain, B. F. and Headon, D. M. (1998). Dietary manipulation as a means of decreasing N losses and methane emissions and improving herbage N uptake following application of pig slurry to grassland. *Journal of Agricultural Science,* 130, 183-191.

Offer, N. W., R. E. Agnew, B. R. Cottrill, D. I. Givens, T. W. J. Keady, C. S. Mayne, C. Rymer, T. Yan, J. France, D. E. Beever. and C. Thomas. (2002). Feed into Milk - An applied feeding model coupled with a new system of feed characterisation. In *Recent Advances in Animal Nutrition,* (Eds. P. C. Garnsworthy and J. Wiseman), Nottingham University Press, Nottingham, pp167-194.

Defra project LK0604 - An improved system for characterising ruminant feeds leading to the development of a nutritional model for dairy cows.

Defra project IS0214 - New integrated dairy production systems: specification, practical feasibility and ways of implementation.

Method 34 – Adopt phase feeding of livestock

Direction of change for target pollutants for phase fed livestock.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	~	~	↓	↓	↓*	~

* From ruminants (and to a lesser extent pigs).

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✗	✓	✗	✗	✓	✗	✗*	✗

* Standard practice in farm ‘baseline’.

Description:
- Manage livestock in smaller groups, divided on the basis of their individual feed requirements.
- Feed groups separately with rations matched to the optimum N and P requirements of the animals within each group.

Rationale: Phase feeding allows more precise matching of the ration to the individual animal’s nutritional requirements. Nutrients are utilised more efficiently and less dietary N and P is excreted, thereby reducing the N and P content of manures, which reduces the amount of N and P at risk of loss.

Mechanism of action: Livestock at different growth stages or stages of their reproductive/lactation cycle, have different optimum feed requirements. However, because of limited labour and housing facilities, livestock with different feed requirements are often grouped together and receive the same ration. As a result, some stock will receive higher levels of N and P than they can utilise efficiently and will excrete the surplus (see Method 33). Greater division and grouping of livestock on the basis of their feed requirements allows more precise formulation of individual rations. This will reduce N and P surpluses in the diet and reduce the amounts excreted.

Potential for applying the method: This method is applicable to all livestock systems, except those primarily based on grazing.

Practicability: The method is most suited to larger units, where there would be greater numbers of animals in individual feeding groups. Also, it would be most effective if adopted in combination with Method 33 ‘reduce dietary N and P intakes’.

In the ruminant sector, this method reflects current practice where dairy cows are grouped according to milk yield. However, practical application can be difficult on some dairy units where cows are fed a single diet across all yields. There is potential for phase feeding in the pig sector to reduce N and P excretion. There is limited scope for improvement in the poultry sector, where phase feeding is already widely used.

Likely uptake: Low in the pig sector, without financial incentives. Uptake is already moderate-high in the dairy sector.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Mixed	Indoor pigs	Costs based on the purchase of capital equipment and are amortised.
Annual	1,800	350	1,250	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 5%, and direct and indirect N_2O emissions, and NH_3 emissions (by up to 5%).

P: Soluble P losses would be reduced by up to 10% and in the longer-term particulate P losses.

Other pollutants: There may be a decrease in CH_4 emissions from ruminants (depending on the diet formulation). Impacts on other pollutants are likely to be minimal.

Key references:

Del Prado, A. and D. Scholefield. (2008). Use of SIMSDAIRY modelling framework system to compare the scope on the sustainability of a dairy farm of animal and plant genetic-based improvements with management-based changes. *Journal of Agricultural Science,* 146, 1-17.

Defra project IS0214 - New integrated dairy production systems: specification, practical feasibility and ways of implementation.

Defra project WA0301 - Dietary manipulation to reduce nitrogen excretion by pigs.

Defra project WA0304 - Dietary manipulation to reduce nitrogen excretion by dairy cattle.

Defra project WA0305 - Alternative strategies for reducing nitrogen pollution from dairy cows.
Defra project WA0306 - Manipulation of nitrogen and phosphorus utilisation in dairy cows.
Defra projects WA0309 and WA0317 - Phase feeding of pigs to reduce nutrient pollution.

Method 35 – Reduce the length of the grazing day/grazing season

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	↑	↓	(↑)	↑

( ) Uncertain estimate.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	×	×	×	×

Description: Reduce the length of time livestock graze in the fields, either by keeping stock inside during the night or by shortening the length of the grazing season.

Rationale: Urine patches are a major source of NO_3 leaching and N_2O emissions to air. Reducing the time animals spend at grazing reduces the amount of urine deposited in fields.

Mechanism of action: Urine patches deposited by grazing livestock contain high concentrations of NH_4-N and act as 'hotspots', with high losses of leached NO_3 and emitted N_2O. Urine deposited later in the season, when there is little opportunity for the grass sward to utilise the added N, make the greatest contribution to NO_3 leaching losses. Therefore, implementing this mitigation method in autumn will have the greatest benefit, as collected excreta can be returned to the fields in a more uniform (and less concentrated form) via slurry spreading. The method will also reduce particulate P/sediment and FIO losses from excreta deposited directly in the field.

Potential for applying the method: The method is applicable to livestock farms where animals graze outside between spring and autumn, and where there is suitable housing.

Practicability: Reducing the length of the grazing day/season is most suited to dairy farms, where cows can be kept indoors. However, this will increase the time that animals are housed and associated labour, manure management and forage production costs.

Likely uptake: Low-moderate, due to additional labour and associated costs.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs based on additional forage production and manure management activities (assuming a 20% reduction in the duration of grazing).
Annual	5,250	3,500	2,200	1,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 20% and direct and indirect N_2O emissions. However, NH_3 emissions would be increased by up to 20% through greater housing, storage and land spreading emissions.

P and sediment: Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of poaching damage.

FIOs and BOD: Losses would be reduced as less excreta is deposited directly in the field.

Other pollutants: CH_4 emissions would increase as greater amounts of manure are stored. CO_2 emissions would increase as a result of greater forage production and manure management activities.

Key references:

Cuttle, S.P. and Scholefield, D. (1995). Management options to limit nitrate leaching from grassland. *Journal of Contaminant Hydrology,* 20, 299-312.

Defra project NT1602 - Understanding the grassland nitrogen cycle in order to improve fertiliser recommendations.

Defra project NT1902 - Control over losses of nitrogen from grassland soils.

Method 36 – Extend the grazing season for cattle

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	↑	↑	↑	↑	↑	↓	↑	(↓)	↓

( ) Uncertain estimate.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	×	×	×	×

Description: Where soil conditions allow, the grazing season is extended (either earlier in the spring or later in the autumn).

Rationale: Urine deposition by cattle at grazing rapidly infiltrates into the soil and is therefore associated with lower NH_3 emissions, compared with higher emissions from urine deposition on concrete floors within cattle housing (and associated emissions during storage and following manure spreading).

Mechanism of action: When cattle are grazing at pasture, excreta returns (urine and faeces) are deposited directly in the field. NH_3 emissions derive predominantly from the urea content of the urine, which must first be hydrolysed to ammonium carbonate before NH_3 emissions can occur. Urine will generally rapidly infiltrate into pasture land and hydrolysis will occur within the soil. The soil presents a physical (by reducing air movement) and chemical (by binding NH_4) barrier to NH_3 emissions, compared with urine deposited on a concrete (impermeable) floor in cattle housing.

Potential for applying the method: This method can be applied to all farms where cattle are housed, however, *soil conditions are likely to limit the potential of the method on many farms* because of unacceptable soil damage through poaching.

Practicability: The method is unlikely to be favoured by high output dairy farmers who like to closely control herd nutrition (see Methods 33 and 34). However, split herds may be operated, where lower yielders/dry cows and followers are managed on an extended grazing system, and the higher yielders are housed. Also, many farmers may be unwilling to risk the sward damage and soil compaction that can be associated with grazing under marginal conditions.

Likely uptake: Low, limited by suitable soil types and climate. Lower output systems may extend the grazing season, thereby avoiding the costs associated with forage production and storing/handling additional amounts of manure. High output systems are less likely to adopt the method.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costings based on the reduced need for forage production and manure management activities (assuming a 20% increase in duration of grazing).
Annual	-1,300	-250	-250	-250	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be increased by up to 20%, and direct and indirect N_2O emissions. However, NH_3 emissions would be reduced by up to 20%, through lower emissions at grazing.

P and sediment: Particulate/soluble P and associated sediment losses would be increased by up to 10%, as a result of greater poaching damage.

FIOs and BOD: Losses would be increased as more excreta is deposited directly in the field.

Other pollutants: CH_4 emissions would reduce as smaller amounts of manure are stored. CO_2 emissions would reduce as a result of lower forage production and manure management activities.

Key references:

Webb, J., Anthony, S. G., Brown, L., Lyons-Visser, H., Ross, C., Cottrill, B., Johnson, P. and Scholefield, D. (2005). The impact of increasing the length of the cattle grazing season on emissions of ammonia and nitrous oxide and on nitrate leaching in England and Wales. *Agriculture Ecosystems & Environment,* 105, 307-321.

Method 37 – Reduce field stocking rates when soils are wet

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	↑	↓	(↑)	↑

( ) Uncertain estimate.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	×	×	×	×

Description: When soils are 'wet', the number of livestock per unit area and/or the time stock spend in the field is reduced to avoid (severe) poaching and compaction of the soil.

Rationale: Soils are most easily poached/compacted when they are 'wet'. Reducing livestock numbers or the duration of grazing when soils are 'wet' reduces poaching damage and the potential for mobilisation and transport of pollutants to watercourses.

Mechanism of action: Poaching/compaction reduces soil water infiltration rates and increases the risk of surface runoff. Lower stocking rates will also reduce the amount of excreta deposited and pollutant amounts available for loss.

Potential for applying the method: This method is applicable to all livestock farms where animals are kept outside and is particular to those with high stocking rates, where extended grazing is practised or where stock are wintered outdoors. Poaching is likely to be more severe with cattle grazing than sheep. Medium/heavy soils are most susceptible to poaching, particularly in high rainfall areas.

Practicability: Implementation will be easier on farms with access to freely draining soils that can provide alternative grazing ground during 'wet' periods, and where there is alternative housing available.

Likely uptake: Low-moderate, due to added labour and associated forage production/manure costs.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs based on additional forage production and manure management activities (assuming a 20% reduction in the duration of grazing).
Annual	5,200	3,500	2,200	1,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 20% and direct and indirect N_2O emissions. However, NH_3 emissions would be increased by up to 20% through greater housing, storage and land spreading emissions.

P and sediment: Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of poaching damage.

FIOs and BOD: Losses would be reduced as less excreta is deposited directly in the field.

Other pollutants: CH_4 emissions would increase as greater amounts of manure are stored. CO_2 emissions would also increase as a result of greater forage production and manure management activities.

Key references:

Defra project NT1002 - Sheet erosion and phosphate loss
Defra project NT1004 - Phosphorus loss from agriculture
Defra project NT1005 - Phosphorus loss from grassland soils
Defra project NT1013 - Phosphorus loss in surface runoff from different land uses
Defra project NT1028 - Measurements of phosphorus loss from manures
Defra project PE0102 - Rationalising risk and scaling-up of on-farm practices to classify rates of phosphorus transfer to grassland catchments

Method 38 – Move feeders at frequent intervals

Direction of change for target pollutants on grazed grassland area.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✗	✓	✗	✗

Description: Feed troughs, feeding racks etc. for outdoor stock are re-positioned at regular intervals to reduce damage to the soil; they should be moved more frequently when the soil is ‘wet’ and most easily poached. They should not be sited close (i.e. within 10m) to water courses.

Rationale: Regular re-positioning of feeding troughs/racks reduces poaching around these points and reduces the quantity of excreta deposited in any single area, both of which can exacerbate diffuse pollution losses in surface runoff.

Mechanism of action: Animal movements in fields concentrate around feeding points that result in large inputs of excreta deposited on these areas, which can be a source of high levels of nutrient and FIO losses to water. As a result of frequent treading, soils around these positions also get heavily poached, which further increases the risk of surface runoff and diffuse pollution losses. Also, damage to the grass sward has the secondary effect of reducing plant uptake that would otherwise reduce NO_3 losses. Moving feeders frequently prevents the accumulation of elevated nutrients and FIOs in localised areas, and reduces the severity of poaching.

Potential for applying the method: The method is most applicable to beef/sheep systems (particularly where livestock are wintered outside) and outdoor pigs. The potential to reduce poaching will be greatest for beef/sheep systems on medium/heavy soils. In all cases, feeders should be located away from watercourses to break the hydrological link between the poached area and surface water

Practicability: The regular re-positioning of feeding troughs is a simple method, with few limitations to implementation. The method will be most effective when applied in combination with Method 37 - ‘reduce field stocking rates when soils are wet’.

Likely Uptake: Moderate-high. A simple method, though regular management is needed to be effective.

Cost:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Out Pigs	Costs based on moving feeders fortnightly and are amortised.
Annual	300	120	100	300	450	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small amount (<2%). Direct and indirect N_2O emissions and NH_3 emissions would also be reduced, as a result of less soil compaction/poaching.

P and sediment: Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of ‘severe’ poaching damage.

FIOs and BOD: Losses would be reduced as a result of less surface runoff.

Other pollutants: CH_4 emissions would be reduced from lower amounts of compaction/poaching damage. CO_2 emissions would increase by a small amount as a result of greater feeding trough movements.

Method 39 – Construct water troughs with a firm but permeable base

Direction of change for target pollutants on the grazed grassland area.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	×	×	×	×

Description: Construct water troughs with a firm base to reduce poaching damage to the soil.

Rationale: Using a firm, yet permeable base reduces poaching of the soil around water troughs.

Mechanism for action: Animal activity is concentrated around drinking points that results in large inputs of excreta to these areas, which can be a source of nutrient and FIO losses to water. Also, soils around water troughs get heavily poached, which further increases anaerobicity and the risks of surface runoff and diffuse pollution. Also, damage to the sward has the secondary effect of reducing plant uptake that would otherwise reduce NO_3 losses. Water troughs, with a firm yet permeable base, reduce poaching and allow the rapid infiltration of urine, reducing the risks of surface runoff and transfer of pollutants to watercourses.

Potential for applying the method: This method is applicable to all beef/sheep/dairy systems where livestock are grazed. The potential to reduce poaching will be greatest on medium/heavy soils.

Practicality: The construction of the permeable base is relatively straightforward. If it is necessary to move an existing trough, there will be a need to install new pipe work.

Likely uptake: Moderate. In ECSFDI catchments grants are available for installing permeable bases for livestock water troughs (and feeders).

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs based on construction of a permeable base and are amortised.
Annual	700	250	200	700	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small amount (<2%). Direct and indirect N_2O emissions and NH_3 emissions would be reduced, as a result of less soil compaction/poaching.

P and sediment: Particulate/soluble P and associated sediment losses would be reduced by up to 10%, as a result of lower amounts of ‘severe’ poaching damage.

FIOs and BOD: Losses would be reduced as a result of less surface runoff.

Other pollutants: CH_4 emissions would be reduced due to lower amounts of compaction/poaching damage. CO_2 emissions would increase by a small amount as a result of base construction.

Method 40 – Low methane livestock feeds

Direction of change for target pollutants for ruminants fed on low methane diets.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	~	~	~	~	~	~	~	↓	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✗	✗	✗	✗

Description: Formulate livestock rations to minimise potential for enteric CH_4 production.
Rationale: Developing a low CH_4 diet for ruminants could significantly reduce CH_4 emissions - enteric fermentation accounts for *c.*80% of CH_4 emissions from agriculture.
Mechanism of action/detection: *In vitro* techniques can be used to measure CH_4 production under rumen-like conditions in the laboratory. One such method (the gas production technique) uses rumen fluid as an inoculum, with CH_4 production following the incubation of a wide variety of feeds measured. Furthermore, the use of near-infrared spectroscopy (NIRS) to predict CH_4 production from specific feedstuffs offers potential for more rapid and cheaper assessments of CH_4 production. However, the results from these techniques do not correlate well with *in vivo* measurements. Notably, there is presently no way of knowing how much CH_4 is produced by a ruminant from a given diet, unless it is fed to the animal and measured using direct or indirect calorimetric techniques.
Potential for applying the method: Any method that could predict CH_4 emissions from specific feeds could be incorporated into a ration formulation system to minimise CH_4 outputs.
Practicability: A laboratory-based method would be relatively easy to implement, particularly as the composition of most feeds is now predicted using NIRS. However, the interaction between different feeds when fed to an animal makes the prediction of CH_4 production from complete diets difficult.
Likely Uptake: This method is under development, but uptake is potentially moderate to high.
Effectiveness:
Methane: Until the potential for adjusting ruminant diets to produce low CH_4 emission feeds is assessed, it is difficult to estimate the potential for reducing CH_4 emissions from enteric fermentation. *Note:* Work is ongoing in Defra project AC0115 to evaluate and develop low CH_4 diets for ruminant livestock.
Other Pollutants: Impacts on other pollutants are likely to be minimal; unless the low CH_4 diet increased feed use efficiency (and thereby associated reductions in N & P excretion).
Key references:

Defra project AC0209 - Ruminant nutrition regimes to reduce methane and nitrogen emissions.
Defra project CC0220 - Use of laboratory procedure for estimating the methane potential of diets.
Defra project AC0115 - Improved National Inventory – Methane.

Method 41 – Reduce overall stocking rates on livestock farms

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	✓	✓	✓	×

Description: Reduce the total number of livestock on the farm i.e. the number of stock per unit of land area.

Rationale: Reducing the stocking rate reduces the amount of nutrients and FIOs in field deposited excreta and in handled manures at an individual farm level. Associated manufactured fertiliser inputs and poaching risks would also be reduced.

Mechanism of action: Livestock excreta deposited in the field and applied in handled manures are important sources of N, P and FIOs; reducing the number of stock will reduce the amounts of excreta and manure produced per unit area. As a result of lower stocking rates on cattle/outdoor pig farms, there will be fewer urine patches and less NO_3 available for loss by leaching or N_2O emission, and poaching risks will be reduced. A smaller number of animals will also produce less manure, which could ease pressures on manure storage capacity and provide greater flexibility for application to avoid high-risk times (Method 26). As the farm will need to produce less forage, manufactured fertiliser rates would also be reduced.

Potential for applying the method: The method is potentially applicable to all livestock farms, and in particular more intensively stocked units that produce large quantities of excreta and manure. The method would also apply to indoor pig and poultry units, as less manure would be produced.

Practicability: The method would be relatively simple to implement, but would have a *serious impact* on farm profitability. Some high output dairy farms could convert to a more extensive dairy system or beef/sheep farming. A moderate reduction in the overall stocking rate could also be achieved on dairy farms by reducing the cow replacement rate, so that fewer young stock are kept on the farm.

Notably, reducing stock numbers is likely to encourage farmers to become more reliant on clover-based swards to reduce manufactured fertiliser N costs. *Note:* The farm manure N loading rate limit in Nitrate Vulnerable Zones of 170 kg/ha total N (Defra/EA, 2008) is effectively a stocking rate limit.

Likely Uptake: Very low, due to the *large negative impact* on overall farm profitability.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Indoor Pigs	Out Pigs	Poultry	Loss in gross margin (through a 20% reduction in livestock numbers) and associated inputs.
Annual	11,000	8,000	5,000	6,000	33,000	19,000	17,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 20% and direct and indirect N_2O emissions, and NH_3 emissions.

P and sediment: Particulate/soluble P and associated sediment losses would be reduced by up to 30%.

FIOs and BOD: Losses would be reduced by up to 20%.

Other pollutants: CH_4 and CO_2 emissions would be reduced by up to 20%

Key references:

Cuttle, S.P. and Scholefield, D. (1995). Management options to limit nitrate leaching from grassland. *Journal of Contaminant Hydrology,* 20, 299-312.

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Defra projects NT1602/NT1902 - To develop strategies to reduce N loss from grassland.

Defra project NT1806 - To develop a predictive capacity for N loss from grassland.

Method 42 – Increase scraping frequency in dairy cow cubicle housing

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓	↑	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	×	✓	×	×	×	×	×	×

Description: Increase the number of times that cubicle passages are scraped from twice to three (or more) times per day.

Rationale: More frequent removal of urine and faeces from the cubicle passage floor reduces the amount of time that NH_3 emissions (from a given quantity of excreta) will occur, thereby reducing the overall potential for emissions.

Mechanism of action: NH_3 emissions from dairy cow cubicle housing predominantly occur from urine, following hydrolysis of the urea content to NH_4-N, through the action of the ubiquitous urease enzyme. More frequent removal of urine and faeces by scraping will increase the proportion of excreta removed from the floor surface (prior to hydrolysis) and also leave a smaller 'pool' of material from which NH_3 emissions occur at any one time. Also, a build-up of dung on the floor can impede the natural drainage of urine, so more frequent removal will also increase the volume of urine reaching the slurry store by natural drainage and thereby further reduce emissions.

Potential for applying the method: The method is applicable to cattle housing with scraped passages, but is best suited to those with a gently sloping floor to assist the rapid drainage of urine. Some modern houses are already fitted with automatic scraper belts.

Practicability: For tractor-scraped systems, increasing the frequency of scraping will require labour that might otherwise be employed elsewhere on the farm. There should be no practical limitations to operating automatic scraper systems in a frequent removal mode. It may be possible to retro-fit automatic scraper systems to some existing dairy cow cubicle houses.

Note: It is important to use this method in combination with Method 54 – 'install covers on slurry stores', Method 55 – 'allow cattle slurry to develop a natural crust' and Methods 70 or 71 at land spreading.

Likely Uptake: Low to moderate.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Mixed	Costs based on one extra cleaning, including labour and tractor operation.
Annual	5,500	2,300	

Effectiveness:

N: NH_3 emissions would be reduced by up to 20% (from cubicle housing). However, as a result of the greater readily available (i.e. NH_4) N content of the slurry, NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other pollutants: CO_2 emissions would be increased by a small amount through the additional scraping operation. Impacts on other pollutants are likely to be minimal.

Key references:

Braam, C. R., Ketelaars, J. and Smits, M. C. J. (1997). Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. *Netherlands Journal of Agricultural Science,* 45, 49-64.

Method 43 – Additional targeted straw-bedding for cattle housing

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	~	~	~	~	↓↓	(↓)	~	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	×	×	×	×

Description: Add 25% extra straw bedding to the cattle house and target the additional straw to ‘wetter/dirtier’ areas of the house.
Rationale: Increasing straw bedding use will enhance the physical and microbiological emissions reduction properties of FYM.
Mechanism of action: Straw bedding reduces NH_3 emissions from cattle housing by providing a physical barrier between urine (which has infiltrated into the bedding) and the air above the bedding, and by encouraging microbial immobilisation of NH_4 (readily available) N. Adding 25% additional straw above standard practice enhances these effects, particularly when the additional straw is specifically targeted to the ‘wettest/dirtiest’ areas of the house (e.g. around water or feeding troughs). Further reductions may be achieved by using even more additional bedding, but there is a risk that too much bedding could cause the litter temperature to rise (due to greater aeration and associated oxygen supply) and actually lead to an increase in NH_3 emissions.
Potential for applying the method: The method is applicable to all cattle farms where a solid manure system is used.
Practicability: The method involves buying, storing and handling additional straw. Greater quantities of FYM will also be generated which will need storing and spreading, and there may be a requirement to remove manure from the building on more occasions over the housing period if the bedding depth becomes too great.
Likely Uptake: Low-moderate, due to the additional cost and limited availability of extra straw, and the associated increase in FYM to be handled.
Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs based on the need to purchase additional straw bedding and to spread additional FYM.
Annual	700	1,200	1,400	900	

Effectiveness:
N: NH_3 emission reductions of up to 50% have been measured from housing; plus lower NH_3 emissions during storage and following land spreading. NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would also be reduced by a small amount.
Other Pollutants: CO_2 emissions would be increased by a small amount because of additional straw use and increased FYM amounts that need to be managed. Impacts on other pollutants are likely to be minimal.
Key reference:
Defra project AM0103 - Evaluation of targeted or additional straw use as a means of reducing ammonia emissions from buildings for housing pigs and cattle.

Method 44 – Washing down dairy cow collecting yards

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓	↑	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	×	✓	×	×	×	×	×	×

Description: Dairy cows are 'collected' on concrete yard areas prior to milking. These areas are usually scraped at least once per day to remove excreta. This method involves pressure washing (or hosing and brushing) of the yards immediately following dairy cow use to more effectively remove the excreta.

Rationale: Urine deposited on collecting yard surfaces is a major source of NH_3 emissions. Reducing the quantity of urine on the yard surface and the time it remains there will reduce NH_3 emissions.

Mechanism of action: The urea content of urine is rapidly hydrolysed to form NH_4-N by the urease enzyme, which is present in the faecal deposits of dairy cows. Excreta are typically removed from dairy cow collecting yards once per day (following the morning milking event) by either a hand or tractor-mounted scraper. Scraping has been estimated to remove 60% of the excreta from the yard surface, but still leaves a film remaining from which emissions can occur. The removal of excreta by pressure washing or by hosing and brushing, immediately following each milking event, will remove a greater proportion of excreta from the yard surface (>90%) prior to urea hydrolysis.

Potential for applying the method: The method could potentially be applied to all collecting yards used by dairy cows.

Practicability: The main practical issue is the extra labour involved in cleaning the yard (typically twice per day) and the extra volume of slurry produced from the added water use.

Note: It is important to use this method in combination with Method 54 – 'install covers on slurry stores', Method 55 – 'allow cattle slurry stores to develop a natural crust' and Methods 70 or 71 at land spreading.

Likely Uptake: Low, due to extra labour and slurry/handling.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Mixed	Costs allow for an additional 25 litres of washwater per cow per day, plus labour.
Annual	7,500	1,400	

Effectiveness:

N: NH_3 emissions would be reduced by up to 90% from dairy cow collecting yards. However, as a result of the greater readily available (i.e. NH_4) N content of the slurry, NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount.

Other Pollutants: CO_2 emissions would be increased by a small amount from the additional pressure washing/hosing and brushing operations and greater amounts of slurry handled. Impacts on other pollutants are likely to be minimal.

Key references:

Misselbrook, T. H., Pain, B. F. and Headon, D. M. (1998). Estimates of ammonia emission from dairy cow collecting yards. *Journal of Agricultural Engineering Research,* 71, 127-135.

Misselbrook, T. H., Webb, J. and Gilhespy, S. L. (2006). Ammonia emissions from outdoor concrete yards used by livestock - quantification and mitigation. *Atmospheric Environment,* 40, 6752- 6763.

Method 45 – Outwintering of cattle on woodchip stand-off pads

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	(↓↓)	(↓)	(↓)	~

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✗	✗	✗	✗

Description: For cattle, as an alternative to winter housing in a building, construct purpose-built woodchip pads (including an impermeable liner and drainage collection system), with a feeding area.
Rationale: NH_3 emissions from urine deposition on to a woodchip stand-off pad are likely to be lower than from a concrete yard or a cattle house, because of rapid infiltration into the woodchip matrix.
Mechanism of action: The rapid infiltration of urine into the woodchip medium will increase the physical barrier to NH_3 volatilisation in a similar way to straw bedding in livestock housing (Method 43) and the soil when cattle are at grazing (Method 36). There may also be some direct adsorption of NH_4 by the woodchip medium and microbial immobilisation by the bacterial community within the woodchip pad. Additionally, drainage from the stand-off pad is likely to be lower in volume (because of evaporation losses), N content and dry matter (compared with slurry from cattle housing), and so the potential for NH_3 emissions following land application is likely to be lower, because of more rapid infiltration of the lower dry matter slurry into the soil. Additionally, the (solid) woodchips need periodically to be recycled to land, but present a low runoff risk.
Potential for applying the method: This method is potentially applicable to all beef and dairy farms where cattle are housed (or kept on concrete yards) for at least part of the year.
Practicability: Farmers are unlikely to replace existing cattle housing facilities with stand-off pads, but may install them where they are expanding herd numbers, but have insufficient housing, or where they currently outwinter a proportion of their cattle.
Likely Uptake: Low-moderate.
Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs based on excavation, drainage, liner (materials and installation) and woodchip inputs, and are amortised.
Annual	7,500	2,500	3,000	2,800	

Effectiveness:
Ammonia: NO_3 (plus ammonium and nitrite) leaching losses are *likely* to be lower as a result of the lower volume and N content of the leachate from the woodchip pads (compared with slurry spreading from cattle housing). Also, NH_3 emissions from the woodchip pad (compared with concrete yards/housing) and NH_3 and direct and indirect N_2O emissions at land spreading are *likely* to be lower.
P: Soluble and particulate P losses are likely to be lower as a result of the lower volume and P content of the leachate from woodchip lads (compared with slurry from cattle housing), as excreta solids (and associated P) are retained in the woodchip matrix.
Other Pollutants: CH_4 emissions are likely to be reduced as stored leachate volumes are lower than from cattle housing and there is likely to be less CH_4 generation from the woodchip matrix than from a slurry store.
Key references:

Smith, K.A., Agostini, F.A. and Laws, J.A. (2005). *Survey of Woodchip Corrals and Stand-off Pads in England and Wales*: *Construction, Operation and Management Practices and Potential Environmental Impacts*. Environment Agency report, 45pp.
LINK project LK0676 – Woodchip pads for sustainable over-wintering of livestock.

Method 46 – Frequent removal of slurry from beneath-slatted storage in pig housing

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓	↑	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✗	✗	✗	✗	✗	✗	✓	✗	✗	✗

Description: Replace slurry storage beneath slats, with frequent removal of slurry to an outside store, using vacuum removal systems operated at least twice per week.

Rationale: NH_3 emissions from slatted-floor pig housing occur from both manure deposited on slat surfaces and also slurry in the below slatted-floor storage area. Frequent removal of beneath-slat slurry will reduce NH_3 emissions from pig housing.

Mechanism of action: This method relies on the removal of slurry as a source of NH_3 emissions from pig housing to an outside store where NH_3 emissions are lower; because of cooler outdoor storage temperatures. A key factor in the success of this method is that the slurry should be removed completely each time (twice per week), otherwise an emitting surface will still be present. NH_3 emissions from outdoor slurry storage can be further reduced by using a store cover (see Method 54).

Potential for applying the method: This method could potentially be applied to all slatted-floor pig housing, subject to sufficient outside storage capacity being available.

Practicability: The method is most suited to purpose-built new installations and could be combined with Method 47 to reduce the emitting surface area. There may be practical difficulties in the retro-fitting of some existing pig housing.

Likely Uptake: Low, due to likely difficulties with the retro-fitting of existing pig housing and the cost of new buildings and slurry storage capacity.

Note: It is important to use this method in combination with Method 54 – 'install covers on slurry stores' and Methods 70 or 71 at land spreading.

Costs:

Total *cost* for farm system (£/farm)	Indoor Pigs	Costs based on additional pumping out from under floor storage and the provision of additional slurry storage, and are amortised.
Annual	11,000	

Effectiveness:

N: NH_3 emissions would be reduced by up to 25% from pig housing. However, there would be a greater readily available (NH_4) N content of the slurry and NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other Pollutants: CO_2 emissions would be increased by a small amount as a result of more frequent slurry removal. Impacts on other pollutants are likely to be minimal.

Key references:

BREF document: European Commission 2003. Integrated Pollution Prevention and Control Reference document on best available techniques for intensive rearing of poultry and pigs.

Method 47 – Part-slatted floor design for pig housing

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓	↑	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	×	✓	×	×	×

Description: Replace fully-slatted floors, with a part-slatted floor, including a domed solid floor area and beneath-slat slurry storage with sloping sides.

Rationale: The method aims to reduce the overall emitting surface area of slurry.

Mechanism of action: NH_3 emissions from pig housing occur from both manure deposited on slat surfaces and also slurry below in the slatted-floor storage area. Providing a solid floor lying area and a slatted-floor dunging area can reduce NH_3 emissions compared with a fully-slatted design. A 50:50 void:floor area (compared with traditional 80:20) can further reduce the fouled floor area. Also, a domed lying area will encourage any deposited urine to quickly drain to the below-slat storage. The ventilation airflow direction is critical to the success of this system, incoming airflows should be drawn downwards to the lying area and then horizontally across the slatted surface. This encourages the pigs to lie on the lying area and dung over the slatted area, and also results in less air mixing above the slatted-floor slurry storage area.

Potential for applying the method: This method is potentially applicable to all slurry-based pig housing.

Practicability: The method is most suited to larger units and to purpose-built *new* installations. The practicality of retro-fitting existing buildings will depend on their design, and would not be possible for many older buildings.

Likely Uptake: Low, due to likely difficulties with the retro-fitting of existing pig housing and the cost of new buildings.

Note: It is important to use this method in combination with Method 54 – 'install covers on slurry stores' and Methods 70 or 71 at land spreading.

Costs:

Total *cost* for farm system (£/farm)	Indoor Pigs	Costs based on solid concrete floor with part-slatting and are amortised.
Annual	13,500	

Effectiveness:

N: NH_3 emissions would be reduced by up to 50% from pig housing. However, there would be a greater readily available (NH_4) N content of the slurry and NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other Pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Defra project WA0720 - Demonstrating opportunities for reducing ammonia emissions from pig housing.

Method 48 – Install air-scrubbers or biotrickling filters to mechanically ventilated pig housing

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓↓	↑	~	↑↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	×	✓	×	×	×

Description: Treat exhaust air from mechanically-ventilated pig housing, using acid scrubbers or biotrickling filters, to remove NH_3.

Rationale: This method removes NH_3 from the exhaust air-stream, thereby reducing emissions to the wider environment.

Mechanism of action: NH_3 is very readily absorbed in low pH solutions. Acid scrubbers typically use sulphuric acid in their recirculation water to ‘capture’ NH_3, as ammonium sulphate, which can then be used on land as a N fertiliser. In biotrickling filters, NH_3 is converted to NO_3 through microbial activity in the biomass held on the synthetic supporting material (organic materials tend to have a short lifetime) and in the recirculation water. As with acid scrubbers, N in the recirculation water can be used on land as a fertiliser.

Potential for applying the method: This method is potentially applicable to all mechanically-ventilated pig housing.

Practicability: The requirement for specific ventilation designs adapted to these specialist treatment technologies, restricts the practical application of this method to *new* purpose-built buildings.

Likely Uptake: Low; only practically applicable to new build sites.

Note: It is important to use this method in combination with Methods 70 and 71 at land spreading.

Costs:

Total *cost* for farm system (£/farm)	Indoor Pigs	Costs based on the installation of air-scrubbers/bio-filters and are amortised.
Annual	32,000	

Effectiveness:

N: NH_3 emissions would be reduced by up to 90% from pig housing. However, there would be a greater readily available (NH_4) N content of the slurry and NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other Pollutants: CO_2 emissions would be increased through additional energy use. Treatment of the exhaust air would also remove other air pollutants (e.g. particulates, odour etc.). Impacts on other pollutants are likely to be minimal.

Key references:

Aarnink, A.J.A., van Hattum, T., Hol, A. and Zhao, Y. (2007). *Reduction of Fine Dust Emission by Combiscrubber of Big Dutchman.* Report No. 66, Animal Sciences Group Wageningen, NL. ISSN 1570-8616.

Method 49 – Convert caged laying hen housing from deep-pit storage to belt manure removal

Direction of change for target pollutants at farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓	↑	↓	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	×	×	×	✓	×

Description: In a deep-pit storage system, manure from laying hens drops in to a pit below the tiered cages where it is stored for a period (of months) prior to removal. This is replaced by a series of belts below each tier of cages, which remove manure from the house (usually on a weekly basis).

Rationale: NH_3 emissions from a deep-pit laying hen house occur from the accumulated manure in the deep-pit storage area. With a belt removal system, operating weekly, most of the NH_3 emissions from a given quantity of manure will occur after the manure has been removed from the house.

Mechanism of action: Birds excrete nitrogen as uric acid (compared to urea from mammals). The hydrolysis of uric acid to NH_4 is generally more prolonged than the rapid hydrolysis of urea, so NH_3 emissions may take one or more days to develop (depending also on temperature and moisture content). Therefore, compared with a deep-pit system where the accumulation of manure will result in continuous and elevated NH_3 emission rates, those from a belt removal system will be substantially lower, as a result of more frequent removal from the house to a lower surface area outdoor storage heap.

Potential for applying the method: This method is potentially applicable to all deep-pit laying hen systems.

Practicability: The method is most appropriate to new build units. The practicalities of converting existing buildings will depend on their design and age.

Likely Uptake: Low, due to likely difficulties with retro-fitting existing laying hen housing.

Note: It is important to use this method (where appropriate) in combination with Method 73 – ‘incorporate manure into the soil’.

Costs:

Total *cost* for farm system (£/farm)	Poultry	Costs based on installation of new cages and belts and are amortised.
Annual	15,000	

Effectiveness:

N: NH_3 emissions from laying hen houses with belt clean systems are around 50% lower than from deep-pit laying hen houses. However, there would be greater readily available (i.e. NH_4 and uric acid) N content of the layer manure and NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other Pollutants: Air quality (including odorant concentrations) within the house should be improved. Impacts on other pollutants are likely to be minimal

Key references:

Nicholson, F. A., Chambers, B.J., and Walker, A. W. (2004). Ammonia emissions from broiler litter and laying hen manure management systems. *Biosystems Engineering,* 89, 175-185.

Defra project WA0651 - Ammonia fluxes within broiler litter and layer manure management systems.

Method 50 – More frequent manure removal from laying hen housing with belt clean systems

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓	↑	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	×	×	×	✓	×

Description: Laying hen houses with manure belts typically operate weekly manure removal. This method increases the frequency of manure removal to twice weekly.

Rationale: The method relies on the rapid removal of manure from the house prior to the peak rate of NH_3 emission.

Mechanism of action: Birds excrete nitrogen as uric acid (compared with urea from mammals). The hydrolysis of uric acid to NH_4 is generally more prolonged than the rapid hydrolysis of urea, so NH_3 emissions may take one or more days to develop (depending also on temperature and moisture content). For a weekly manure removal system, measurements have shown that NH_3 emissions can increase substantially on the last two days prior to manure removal. Twice weekly manure removal will therefore remove the emitting source prior to the peak emission.

Potential for applying the method: This method is potentially applicable to all laying hen houses with belt systems for manure removal.

Practicability: There should be few (or no) practical reasons why this method could not be adopted by farmers with belt manure removal systems.

Likely Uptake: High. The method involves a doubling in manure removal frequency and associated labour/energy costs.

Note: It is important to use this method (where appropriate) in combination with Method 73 – ‘incorporate manure into the soil’.

Costs:

Total *cost* for farm system (£/farm)	Poultry	Costs based on a small increase in energy use.
Annual	250	

Effectiveness:

N: NH_3 emissions would be reduced by *c.*50% compared with weekly manure removal. However, there would be a greater readily available (i.e. NH_4 and uric acid) N content of the layer manure and NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other Pollutants: CO_2 emissions would be increased by a small amount through additional energy use. Air quality (including odorant concentrations) within the house should be improved. Impacts on other pollutants are likely to be minimal.

Key references:

Nicholson, F. A., Chambers, B. J. and Walker, A. W. (2004). Ammonia emissions from broiler litter and laying hen manure management systems. *Biosystems Engineering,* 89, 175-185.

Defra project WA0651 - Ammonia fluxes within broiler litter and layer manure management systems.

Method 51 – In-house poultry manure drying

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓	↑	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	×	×	×	✓	×

Description: Install ventilation/drying systems to reduce the moisture content of laying hen manure (in deep-pit or on belts) or poultry litter within the house.

Rationale: Drying will inhibit the hydrolysis of uric acid N in the manure, slowing the formation of NH_4-N and thereby reducing NH_3 emissions.

Mechanism of action: Birds excrete nitrogen as uric acid, which is subsequently converted to NH_4-N by hydrolysis. Drying the manure/litter to achieve a dry matter content of 60-80% will greatly reduce the rate of hydrolysis.

Potential for applying the method: This method is potentially applicable to all poultry housing systems.

Practicability: Most laying hen houses with belt-removal or deep-pit systems should be suitable for the retro-fitting of drying systems. For broiler housing, the practicalities of installing forced manure drying to a litter-based system will depend on the existing building design and age; many buildings are likely to have practical limitations.

Likely Uptake: Low-moderate, due to practical limitations.

Note: It is important to use this method (where appropriate) in combination with Method 73 – ‘incorporate manure into the soil’.

Costs:

Total *cost* for farm system (£/farm)	Poultry	Costs based on the installation and running of drying equipment, and are amortised.
Annual	1,000	

Effectiveness:

N: NH_3 emissions would be reduced by up to 50% from the poultry housing. However, there would be a greater readily available (i.e. NH_4 and uric acid) N content of the poultry manure, and NH_3 emissions during storage and following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other Pollutants: CO_2 emissions would be increased by a small amount through additional energy use. Air quality (including odorant concentrations) within the house should be improved. Impacts on other pollutants are likely to be minimal

Key references:

Smith, K.A., Jackson, D.R. and Metcalfe, J.P. (2001). Low cost aerobic stabilisation of poultry layer manure. In: *Sustainable Handling and Utilisation of Livestock Manure from Animals to Plants*, Proceedings of NJF Seminar No 320 (Eds. Rom, H.B. and Sorenesen, C.G.), Danish Institute of Agricultural Sciences Report No 21, Animal Husbandry.

Defra project WA0638 - Low cost aerobic stabilisation of poultry layer manure.

Method 52 – Increase the capacity of farm slurry (manure) stores to improve timing of slurry applications

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓↓	~	↓	↓	↑	(↓)	(↑)	~

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✗	✓	✗	✗	✓	✗	✗	✗

Description: On farms where there is currently limited slurry storage capacity, expand facilities for the collection and storage of slurry, to allow spreading at times when there is a low-risk of runoff and when there is an actively growing crop to utilise nutrients applied in the slurry.

Rationale: The collection and storage of slurry provides increased flexibility in land application timing. There will be fewer occasions when a lack of storage capacity forces slurry application to occur when here is a high-risk of surface runoff or drainflow losses to water i.e. when soils are ‘wet’.

Mechanism of action: If a farm has little or no storage capacity for slurry, this will inevitably result in applications at times when there is a risk of surface runoff or drainflow losses of nutrients, FIOs and BOD. Adequate storage facilities provide greater freedom in choosing when to apply slurry to fields.

Potential for applying the method: The method is applicable to livestock farms that have limited slurry (manure) storage facilities; the provision of adequate storage facilities is most important on farms that handle their manure as slurry. Solid manures can be stored in the animal house or in field heaps, prior to land spreading, at a time of year that presents a lower risk of pollution.

Practicability: The method will be most effective if implemented in conjunction with Methods 54/55 which will reduce NH_3 emissions from slurry storage, and Methods 68 and 70/71 that will reduce diffuse pollution risks following land spreading.

Likely Uptake:

Costs:

Total *cost* for farm system (£/farm)	Dairy	Mixed	Indoor Pigs	Costs based on construction of additional slurry storage and are amortised.
Annual	2,000	5,000	1,500	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 10% and associated indirect N_2O emissions. However, NH_3 emissions would be increased by a small amount due to an increase in the slurry store surface area and application to ‘dry’ soils in the summer period, and direct N_2O emissions would also decrease by a small amount from increased soil mineral N levels. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs would be reduced.

P: Particulate and soluble P losses would be reduced by up to 20% through avoiding slurry application to ‘wet’ soils when runoff risks are high.

FIOs and BOD: Losses would be reduced through avoiding slurry application to ‘wet’ soils.

Other Pollutants: CH_4 emissions would be increased as a result of increasing the duration of slurry storage.

Key references:

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Lord, E.I., Shepherd, M.A., Silgram, M, Goodlass, G., Gooday, R, Anthony, S.G., Davison, P. and Hodgkinson, R. (2007). *Investigating the Effectiveness of NVZ Action Programme Measures: Development of a Strategy for England*. Report for Defra Project NIT18.

Thorman, R.E., Sagoo, E., Williams, J.R., Chambers, B.J., Chadwick, D.R., Laws, J.A. and Yamulki, S. (2007). The effect of slurry application timings on direct and indirect N_2O emissions from free draining grassland soils. *In: Towards a Better Efficiency of N Use*. (Eds. Bosch, A.D., and Villor, J.M.), 15th Nitrogen Workshop, Spain, pp.297-299.

Defra project ES0106 - Developing integrated land use and manure management systems to control diffuse nutrient losses from drained clay soils: BRIMSTONE-*NPS*.

Defra project ES0115 - Optimising slurry application timings to minimise nitrogen losses: OPTI-*N*.

Method 53 – Adopt batch storage of slurry

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	~	~	~	↓	↓↓	↑	~	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✗	✓	✗	✗	✓	✗	✗	✗

Description: Store slurry in batches for at least 90 days before land spreading; do not add fresh slurry to the store during this storage period.

Rationale: FIOs die-off during storage. However, adding fresh slurry results in re-inoculation with viable microorganisms, so for effective reduction in FIO loads, slurry needs to be batch stored without fresh additions. As there are few microorganisms on the batch stored slurry (after 90 days), the risk of FIOs entering water bodies *via* surface runoff or drainflow losses (after slurry application) is greatly reduced.

Mechanism of action: Numbers of FIOs decline during storage, which can be an effective means of reducing microbial pathogen numbers in slurry. If there is any surface runoff or drainflow soon after slurry application FIOs losses will be lower compared with ‘fresh’ slurry.

Potential for applying the method: This method is potentially applicable to all livestock farms that produce slurry.

Practicability: The method needs slurry to be stored without any fresh additions for 90 days, which will require (at least) two stores.

Likely Uptake: Low, due to the need for (at least) two slurry stores.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Mixed	Indoor Pigs	Costs based on the construction of additional slurry storage and are amortised.
Annual	2,500	500	2,500	

Effectiveness:

N: NH_3 emissions would be increased by a small amount as a result of the greater slurry store surface area.

FIOs and BOD: FIO loss risks to surface water would be reduced by > 90% and BOD losses by up to 50% from managed slurry.

Other Pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Nicholson, F.A., Groves, S. and Chambers, B.J. (2005). Pathogen survival during livestock manure storage and following land application. *Bioresource Technology*, 96, 135-143.

Defra project WA0656 - Implications of potential measures to control pathogens associated with livestock manure management.

Method 54 – Install covers on slurry stores

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	↓	↓	~	~	~	↓	↑	(↓)	↓

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	×	✓	×	×	✓	×	×	×

Description: Open slurry stores (tanks or lagoons) are fitted with a cover (either a rigid cover with a vent or a floating flexible cover).

Rationale: Covering slurry stores reduces NH_3 emissions and where rainfall is diverted reduces the volume of slurry collected.

Mechanism of action: NH_3 will volatilise from a slurry store surface (the rate depends on factors such as NH_4-N concentration, pH, temperature and air movement) and will be replenished in the surface layer from lower levels in the slurry store. Natural air movement above the store will ensure that the emitted NH_3 is removed and is continually replaced by air with a lower NH_3 concentration. By placing a cover above or on the slurry surface and preventing the removal of emitted NH_3 by advection, a higher NH_3 concentration will soon develop in the enclosed airspace. This higher concentration will reduce further NH_3 emissions from the slurry, so the overall emission rate will decline. Most covers include some vents (to prevent a build up of CH_4), so emissions will not stop entirely, but will be greatly reduced compared with a situation of free air movement above the slurry store. Placing a cover over the slurry store prevents the collection of rainfall (where the rainfall is diverted) and in high rainfall areas can result in a significant reduction in overall slurry volumes.

Potential for applying the method: This method could potentially be applied to all open slurry stores. There may be less benefit in applying the method to cattle slurry stores where natural crusts often develop and give effective NH_3 emission reductions (see Method 55). The method is most relevant to pig and dairy farms that separate slurry liquid: solid fractions.

Practicability: Rigid covers are applicable to concrete and steel tanks, but *may not be suitable* for all existing stores (e.g. where the existing store has insufficient structural support for a rigid cover). Plastic (floating) covers are applicable to tanks and small earth-banked lagoons, but can be difficult to fit and manage on larger lagoons. 'Low technology' floating covers (*e.g.* oilbased liquids, chopped straw, peat, bark, LECA balls etc.) can be used on the surface of tanks, but are less suited to earth-banked lagoons where wind drift can cause problems with retaining a complete surface cover. These covers do not divert rainwater and require management time during store filling, mixing and emptying.

Likely Uptake: Low to moderate, due to cost implications, logistical issues with lagoons and existing tanks with insufficient structural support.

Note: It is important to use this method is used in combination with Methods 70 or 71 at land spreading.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Mixed	Indoor Pigs	Costs based on provision of a store cover and are amortised.
Annual	700	150	500	

Effectiveness:

N: NH_3 emissions from slurry stores have been shown to be reduced from using rigid store covers by 80%, plastic sheeting by 60% and 'low technology' floating covers by 40%. However, as a result of the greater readily available (NH_4) N and higher dry matter content of the slurry, NH_3 emissions following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

P: Particulate and soluble P loss risks would be reduced where the cover diverts rainfall, as lower amounts of slurry would need to be spread.

Other Pollutants: CO_2.emissions would be reduced (where the cover diverts rainfall) as lower amounts of slurry would need to be spread, and CH_4 emissions could also be reduced by a small amount. Odour emissions from the slurry store would also be reduced.

Key references:

Pain, B. and Webb, J. (2002). *Ammonia in the UK*. Chapter II – Overview of research on methods for reducing emission from agriculture. Defra publications, London. PB6865.

Portejoie, S., Martinez, J., Guiziou, F., and Coste, C. M. (2003). Effect of covering pig slurry stores on the ammonia emission processes. *Bioresource Technology,* 87, 199-207.

Scotford, I. M. and Williams, A. G. (2001). Practicalities, costs and effectiveness of a floating plastic cover to reduce ammonia emissions from a pig slurry lagoon. *Journal of Agricultural Engineering Research,* 80, 273-281.

Method 55 – Allow cattle slurry stores to develop a natural crust

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓	↑	(↓)	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	×	✓	×	×	×	×	×	×

Description: Retain a surface crust on stores, composed of fibre and bedding material present in cattle slurry, for as long as possible. In most cattle systems, it is possible to retain an intact crust for the majority of the year.

Rationale: The surface crust acts as a physical barrier between the NH_4-N in slurry and the free air above the crust, and thereby reduces NH_3 emissions.

Mechanism of action: Fibre from undigested plant material and bedding within cattle slurry floats to the surface of the slurry store aided by uprising CH_4 bubbles produced by bacterial action within the slurry. Thereafter, evaporative forces from wind and solar radiation cause the crust to dry, increasing its strength and integrity. The viscosity of the surface layer increases the time taken for NH_4 at the surface emitting layer to be replenished from deeper within the slurry store, and thereby reduces NH_3 emissions.

Potential for applying the method: This method is applicable to all slurry stores with the potential to form a crust; these tend to be cattle slurry stores in the UK (as pig slurry does *not* tend to crust). However, there are circumstances where cattle slurry stores do not form a crust (*e.g.* where they contain dilute or separated slurries).

Practicability: Management of the slurry store in order to maintain an effective crust is critical to the success of this method; regular agitation is therefore not an option, unless it can be achieved without breaking the crust. Some top filling slurry stores may not form a complete crust. Tank emptying can be difficult if the crust becomes too thick and solid, for this reason, it is recommended that the crust is completely broken-up during tank emptying at least once per year.

Likely Uptake: Low; it is estimated that 80% of cattle slurry stores already have natural crusts present.

Note: It is important to use this method in combination with Methods 70 or 71 at land spreading.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Mixed	Costs based on purchasing and running a ‘larger’ stirrer to break up the crust prior to emptying, and are amortised.
Annual	100	50	

Effectiveness:

N: NH_3 emissions during slurry storage have been estimated to be reduced by 50%, compared with non-crusted cattle slurry. However, as a result of the greater readily available (NH_4) N content of the slurry, NH_3 emissions following land spreading would be increased, but by a lower amount. Similarly, NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

Other Pollutants: CO_2 emissions would be increased by a small amount due to the need for more stirring to break-up the surface crust. There is some evidence that CH_4 emissions would be reduced by a small amount, due to microbial oxidation of CH_4, as it passed through the slurry crust. Odour emission would be reduced by the crust. Impacts on other pollutants are likely to be minimal.

Key references:

Misselbrook, T. H., Brookman, S. K. E., Smith, K. A., Cumby, T. R., Williams, A. G. and McCrory, D. F. (2005). Crusting of stored dairy slurry to abate ammonia emissions: pilot-scale studies. *Journal of Environmental Quality,* 34, 411-419.

Petersen, S. O., Amon, B. and Gattinger, A. (2005). Methane oxidation in slurry storage surface crusts. *Journal of Environmental Quality,* 34, 455-461.

Smith K., Cumby, T. Lapworth, J., Misselbrook, T.H. and Williams, A. (2007). Natural crusting of slurry storage as an abatement measure for ammonia emissions on dairy farms. *Biosystems Engineering,* 97, 464-471.

Sommer, S. G., Petersen, S. O. and Sogaard, H. T. (2000). Greenhouse gas emissions from stored livestock slurry. *Journal of Environmental Quality,* 29, 744-751.

Method 56 – Anaerobic digestion of livestock manures

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	↓	↓	(↑)	(↑)	↓	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	×	×	✓	×	✓	×

Description: Use anaerobic digestion (AD) of livestock manures to generate CH_4 for biogas production.

Rationale: CH_4 generated from livestock manures during (mesophilic) anaerobic digestion can be used to produce heat and power, and to replace fossil fuel use. Also, CH_4 emissions during subsequent manure storage prior to land spreading will be reduced

Mechanism of action: Anaerobic digestion of organic materials by microbial populations in a sealed container to generate CH_4 that is used to produce heat and power. During AD, organic N is mineralised to ammonium NH_4 (i.e. readily available) N; typically NH_4-N is increased by around 10% of the total N content. As a result of the digestion process, FIO numbers and BOD and the dry matter of the digestate is reduced

Potential for applying the method: Farms with significant numbers of housed livestock (e.g. pigs and zero-grazed dairy cows) would be most appropriate for on-farm installations.

Practicability: There are significant start-up and running costs for on-farm (and centralised) AD facilities, which discourage the uptake of this technology. Financial incentives are likely to be required to encourage adoption of AD facilities, using livestock manure as a feed source. *Note:* by including food-waste gas yields can be boosted and associated ‘gate-fees’ provide a revenue stream

Likely Uptake: Low, due to poor economics. The availability of capital grants and ‘high’ renewable energy prices would be needed to stimulate on farm AD facilities.

Note: It is important that this method is used in combination with Method 54 – ‘install covers on slurry stores’ and Methods 70 or 71 at land spreading.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Indoor Pigs	Poultry	Costs based on an on-farm AD plant and are amortised.
Annual	13,000	2,800	2,500	15,000	55,000	

Effectiveness:

Methane: CH_4 emissions from slurry storage (post AD) would be reduced, plus heat and power would be produced.

N: An increase in the readily available (NH_4) N content of the digestate would increase NH_3 emissions during storage and most likely following land spreading (although the lower dry matter content of the digestate is likely to increase soil infiltration rates), and associated direct and indirect N_2O emissions. Similarly, NO_3 (plus ammonium and nitrite) leaching losses would be increased by a small amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

FIOs and BOD: Microbial pathogen numbers would be reduced by around 2 logs during mesophilic AD and BOD by around 50%.

Other Pollutants: CO_2 emissions would be increased due to greater energy use in mixing the digestate during AD etc. However, overall greenhouse gas (and energy production) benefits would be positive.

Key references:

ADAS/SAC. (2007). *Nutritive Value of Digestate from Farm-based Biogas Plants in Scotland*. Report for Scottish Executive Environmental and Rural Department (ADA/009/06).

Burton, C.H. and Turner, C. (2003). *Manure Management: Treatment Strategies for Sustainable Agriculture*. Silsoe Research Institute.

Chantigny, M.H., Rochette, P., Angers, D.A., Masse, D. and Cote, D. (2004). Ammonia volatilization and selected soil characteristics following application of anaerobically digested pig slurry. *Soil Science Society of America Journal,* 68, 306-312.

Martinez J., Guiziou F., Peu P. and Gueutier V. (2003). Influence of treatment techniques for pig slurry on methane emissions during subsequent storage. *Biosystems Engineering,* 85, 347-354.
Morgan, J. and Pain, B.F. (2008). Anaerobic digestion of farm manures and other products for energy recovery and nutrient recycling. *International Fertiliser Society Proceedings*, No. 632, 38pp.
Defra project AC0406 - The optimisation and impacts of expanding biogas production.
Defra project AC0206 - A review of the research to identify best practice for reducing greenhouse gases from agriculture and land management.

Method 57 – Minimise the volume of dirty water (and slurry) produced

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	~	~	~	↓

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✓	✗	✓	✗

Description: Minimise the volume of dirty water produced by:

- Minimising unnecessary dirty yard areas.
- Avoiding excessive use of water in washing down yards, buildings, etc.
- Preventing unnecessary mixing with clean water from uncovered clean yard areas, from roofs etc.
- Roofing over yard areas and covering dirty water and slurry stores.

Rationale: Minimising the volume of dirty water produced reduces the volume to be stored and spread. Farms will be less likely to run out of storage space and be forced to spread dirty water (or slurry) at times when there is a high risk of runoff.

Mechanism of action: On some farms, dirty water is collected separately and spread on fields, whereas on others it is added to the main slurry store. Keeping the fouled yard area as small as possible minimises the volume of water required to wash it down and hence the volume of dirty water (or slurry) produced. Roofing such yards would avoid additional inputs from rainwater. Poorly designed or badly maintained drains and gutters can allow rainwater from non-fouled yards and roofs to mix with dirty water (or slurry) and further increase the volume. This clean water should be managed separately e.g. to a soak-away.

Avoiding unnecessary inputs of water reduces the volume of dirty water (or slurry) produced and increases the number of days of storage capacity. This helps to avoid the need to apply dirty water (or slurry) when soils are ‘wet’ and reduces the likelihood of surface runoff and drainflow losses of nutrients and FIOs/BOD to (surface) water systems. Also, covering dirty water and slurry stores prevents rainfall from adding to the volume to be stored.

Potential for applying the method: This method is mainly applicable to farms with cattle, particularly dairy farms; although most livestock farms produce dirty water. Preventing unnecessary inputs of rainwater will be most beneficial in high rainfall areas.

Practicability: There are few limitations to the adoption of this method, although there may be practical issues to the roofing of foul-yards and covering of dirty water stores.

Likely Uptake: Moderate to high, due to the low cost of many of the options. Capital grants are available in ECSFDI priority catchments.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	In Pigs	Poultry	Costs based on roofing of collecting yards and foul-yard areas, and are amortised.
Annual	1,400	500	550	700	1,600	2,200	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching loses would be reduced by a small (<1%) amount due to the better timing of dirty water (slurry) applications; as a result of increased storage capacity.

P: P losses would be reduced by a small amount (<2%) due to the better timing of dirty water (slurry) applications.

FIOs and BOD: Losses would be reduced as result of better timing of dirty water (slurry) applications.

Other pollutants: CO_2 emissions would be reduced as there would be less dirty water (slurry) to be managed. Impacts on other pollutants are likely to be minimal.

Key references:

Defra project ES0106 – Developing integrated land use and manure management systems to control diffuse nutrient loss from drained clay soils: BRIMSTONE-*NPS*.

Method 58 – Adopt (batch) storage of solid manures

Direction of change for target pollutants at the farm scale

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	~	~	~	↓↓	↓	(↓↑)	↑	~

( ) Increased during storage, reduced at land spreading – balance uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✓	✗	✓	✗

Description: Store ‘fresh’ solid manure in separate batches (for at least 90 days) before land spreading.

Rationale: FIOs die-off during storage; as a result there will be fewer microbial pathogens in the spread manure and lower loss risks in runoff. Also, the readily available N content of stored farmyard manure (FYM) is lower than in ‘fresh’ FYM, due to losses during storage, which will lessen the risk of NO_3 leaching losses and NH_3 emissions.

Mechanism of action: FIO numbers decline during solid manure storage, with the rate of decline accelerated if high temperatures (i.e. passive composting) develop in the heap; this happens naturally in most FYM and poultry litter heaps. Hence, there are fewer microbial pathogens in the manure when it is spread and therefore less risk of FIO losses in surface runoff and drainflow. Storage is effective at reducing bacterial numbers, but is less effective in reducing populations of the protozoan parasite, *Cryptosporidium*. There will be gaseous losses of NH_3 and N_2O and immobilisation of N during storage, which will reduce the readily available N content of FYM at the end of storage. ‘Fresh’ FYM typically contains 20-25% NH_4-N compared with 10-15% where FYM has been stored for more than 3 months. There will also be a reduction in the total N amount, with typically 30-50% of total N being lost during FYM storage (either as NH_3, N_2O or di-nitrogen gas, or in leachate). For poultry manure, about 10-15% of total N is lost during storage, but the proportion of readily available N remains similar to that in the ‘fresh’ material (typically in the range 35-50% of total N).

Potential for applying the method: This method is applicable to livestock farms that produce solid manure and apply ‘fresh’ solid manure to land (or where manure is continuously added to existing heaps). *Note:* Around 30% of FYM and 60% of poultry manure is applied ‘fresh’ to land.

Practicability: The method is practical where it is possible to store solid manure in separate field heaps or where it is possible to subdivide an existing store.

Likely Uptake: Moderate – high, where field heaps can be used for batch storage.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Indoor Pigs	Poultry	Costs based on the provision of a concrete base (with pads for vehicle movements) and are amortised.
Annual	250	350	550	1,500	1,800	500	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced as a result of the lower readily available N content of FYM and lower amounts of total N in FYM/poultry manure spread to land, and associated direct and indirect N_2O and NH_3 emissions at land spreading. However, NH_3 (and N_2O) emissions would be increased during storage, but by a lower amount. Effects on the balance of N_2O emissions at the farm scale are uncertain.

FIOs: Losses would be reduced compared with ‘fresh’ manure applications

Other Pollutants: CH_4 emissions would be increased (compared with the application of ‘fresh’ manure to land). Odour emissions would be reduced at land spreading. Impacts on other pollutants are likely to be minimal.

Key references:

Defra (2010). *Fertiliser Manual (RB209)*. 8th Edition. The Stationery Office, Norwich. ISBN 978-0-11-243286-9.

Chadwick, D.R., Matthews, R.A., Nicholson, R.J., Chambers, B.J. and Boyles, L.O. (2002). Management practices to reduce ammonia emissions from pig and cattle manure stores. In: *Proceedings of the 10th International Conference of the FAO RAMIRAN Network on Recycling of*

Agricultural, Municipal and Industrial Residues in Agriculture (Eds. J. Venglovsky and G. Greserova), pp.219-223.

Nicholson, F.A., Groves, S. and Chambers, B.J. (2005). Pathogen survival during livestock manure storage and following land application. *Bioresource Technology*, 96, 135-143.

Sagoo, E., Williams, J.R., Chambers, B.J., Boyles, L., Matthews, R. and Chadwick, D.R. (2004). Integrated management practices to minimise losses and maximise crop nitrogen values of broiler litter. In: *Proceedings of the 11th International Conference of the FAO RAMIRAN Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture* (Eds. Bernal, M.P., Moral, R., Clemente, R. and Paredes, C.), Vol. 1, pp.249-252.

Defra project WA0656 - Implications of potential measures to control pathogens associated with livestock manure management.

Defra project WA0716 - Management techniques to reduce ammonia emissions from solid manures.

Method 59 – Compost solid manure

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	~	~	~	~	↓↓	↓	(↑↓)	↑	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	✓	×	✓	×

Description:

- Encourage the breakdown of solid manure by active composting.
- Turn the solid manure windrow twice in the first seven days of composting to facilitate aeration and the development of high temperatures within the windrow.

Rationale: The aim is to facilitate naturally occurring microflora to degrade cellulose and other carbon compounds in the manure to produce a friable, stable and spreadable material, with reduced volume. As part of the composting process, the manure is ‘sanitised’ and the readily available N content is reduced, thereby lowering the risks of FIO and NO_3 losses when the composted manure is spread to land.

Mechanism of action: Increased temperatures during *active composting* inactivate microbial pathogens and most weed seeds; and reduce the readily available N content of FYM. Composting has little effect on the proportion of readily available N in poultry manure. The readily available N content of FYM is typically reduced from 20-25% (in ‘fresh’ FYM) to 10-15% of total N (in composted FYM). The whole process should be monitoring to ensure that temperatures increase to above 55^{o}C for three days after each turn. Turning of the heap ensures that all parts are treated (i.e. composted).

Potential for applying the method: Applicable to farms with solid manures, particularly where windrows can be established safely in fields or on an impermeable base. Composting typically results in 40-50% of the total N in FYM and around 15-20% in poultry litter being lost (either as NH_3, N_2O or di-nitrogen gas, or in leachate).

Practicability: Can be incorporated into normal farm operations, using standard farm machinery.

Likely Uptake: Low-moderate, most likely where there is an incentive to reduce solid manure volumes prior to transport and spreading, and where sanitation is important prior to land spreading (e.g. in front of ready to eat crops etc.).

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Indoor Pigs	Poultry	Costs based on turning of solid manure windrows twice.
Annual	600	750	1,200	3,500	4,500	2,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced as a result of the lower readily available N content of FYM and lower amounts of total N in FYM/poultry manure spread to land, and associated direct and indirect N_2O and NH_3 losses at land spreading. However, NH_3 emissions would be increased during composting, but by a lower amount. Effects on the balance of N_2O emissions at the farm scale are uncertain.

FIOs: FIOs would be reduced (compared with ‘fresh’ manure application).

Other Pollutants: CH_4 emissions would be increased (compared with ‘fresh’ manure application). CO_2 emissions would be increased by the turning operations. Odour emissions would be reduced at land spreading. Impacts on other pollutants are likely to be minimal.

Key references:

Defra (2010). *Fertiliser Manual (RB209)*. 8th Edition. The Stationery Office, Norwich. ISBN 978-0-11-243286-9.

Defra project WA0656 - Implications of potential measures to control pathogens associated with livestock manure management.

Defra project WA0716 - Management techniques to reduce ammonia emissions from solid manures.

Method 60 – Site solid manure field heaps away from watercourses/field drains

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	~	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✗	✗	✗

Description: Where solid manure is stored in a field heap it should not be sited within 10m of a watercourse or (effective) field drain.

Rationale: Keeping solid manure heaps away from watercourses and field drains reduces the risk of pollutant losses in surface runoff or drainflow.

Mechanism of action: An adequate separation distance between field heaps and watercourses reduces the risk that any leachate from a heap might run over the soil surface directly into a watercourse. Similarly, siting solid manure heaps away from field drains reduces the risk of preferential flow of leachate through the soil that could transport nutrients, FIOs and oxygen depleting pollution to watercourses. There can be an increased risk of surface runoff from the area immediately surrounding a field heap, because of damage to soil structure caused by farm machinery when loading/unloading manure.

Potential for applying the method: This method is applicable to all farms that produce or import solid manure and store it in a field heap, where watercourses and field drains are present. Benefits are likely to be greatest on medium/heavy soils where surface runoff risks are highest and field drains are likely to be present.

Practicability: The method is simple to implement, with few limitations to its use. However, it can be difficult to find suitable positions for field heaps on farms where fields have closely-spaced drains.

Likely Uptake: Moderate-high. This method is a legal requirement in NVZs.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Costs based on added time to carefully plan the location of fields heaps.
Annual	100	150	100	100	100	100	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small (<1%) amount and associated indirect N_2O emissions.

P: P losses would be reduced by a small (<1%) amount.

FIOs and BOD: Losses would be reduced.

Other Pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.
Defra project WA0517 - Impacts of farm waste stores on groundwater quality.
Defra project WA0712 - Management techniques to minimise ammonia emissions during storage and land spreading of poultry manures.
Defra project WA0716 - Management techniques to reduce ammonia emissions from solid manure.
Defra project WA0632 - Ammonia fluxed within solid and liquid manure management systems.

Method 61 – Store solid manure heaps on an impermeable base and collect leachate

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	↑	(~)	~	~

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✓	✗	✓	✗

Description: Manure heaps are sited on an impermeable base, with leachate collection facilities.
Rationale: The impermeable base and leachate collection prevents the direct loss of pollutants in surface runoff and drainflow.
Mechanism of action: If stored directly on the soil surface, leachate from solid manure heaps will seep into the soil and/or flow over the soil surface in response to rainfall events. Storing manure on an impermeable base prevents the seepage and accumulation of nutrients in the soil below the heap, which may subsequently be lost in surface runoff/drainflow or leaching to ground water. Also, storage on an impermeable (e.g. a concrete base) reduces soil compaction caused by farm machinery, during the forming and subsequent spreading of field heaps. The leachate collected can be spread at a later date when soil conditions are suitable and the nutrients can be utilised by crops, or the leachate may be added back to the heap or into a slurry store.
Potential for applying the method: This method is applicable to all livestock farms that produce or import solid manure. Benefits will be greatest on medium/heavy soils where surface runoff risks are highest and where field drains are likely to be present.
Practicability: The cost of constructing solid manure storage facilities, with an impermeable base and leachate collection facilities is the main obstacle to adopting this method.
Likely Uptake: Low, because of the capital costs of construction.
Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Indoor Pigs	Poultry	Costs based on construction of a concrete pad with leachate collection facilities and are amortised
Annual	250	350	550	1,500	1,800	500	

Effectiveness:
N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small (<5%) amount and associated indirect N_2O losses. However, NH_3 emissions would be increased as a result of conserved N in the recycled leachate. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.
P: Soluble/particulate P losses would be reduced by a small (<2%) amount.
FIOs and BOD: Losses would be reduced as the leachate is collected.
Other Pollutants: Impacts on other pollutants are likely to be minimal.
Key references:

Defra project ES0138 - Review of livestock manure management options in European NVZs.
Defra project WA0712 - Management techniques to reduce ammonia emissions during storage and land spreading of poultry manures.
Defra project WA0716 - Management techniques to reduce ammonia emissions from solid manure.

Method 62 – Cover solid manure stores with sheeting

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	↓	(↑↓)	↑	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	×	×	✓	×	✓	×

Description: Solid manure field heaps are covered (e.g. with heavy duty polythene sheeting) in a similar manner to a silage clamp.

Rationale: The sheeting provides a physical barrier preventing the release of NH_3 from the manure heap to the air.

Mechanism of action: NH_3 volatilises from the NH_4-N content of a manure heap and diffuses through the heap into the free air stream above. Covering a heap with polythene sheeting provides a physical barrier, which the NH_3 gas cannot pass through. The cover prevents the advection of volatilised NH_3 away from the heap, so a high NH_3 concentration develops in the air spaces within the heap and between the heap and cover. This high concentration will inhibit further NH_3 emissions from the manure, so the overall emission rate will decline rapidly.

Potential for applying the method: This method could be applied to all solid manures that are stored in heaps. The method will be most effective where used in combination with Method 73 – 'incorporate manure into the soil'.

Practicability: Covering purpose-built manure 'clamps' (as with silage) would represent an ideal solution, but would represent significant investment, if such facilities were not already available. Long, low field heaps which are typical of in-field manure storage prior to land application would require large amounts of sheeting for covering; so heaps should be shaped to minimise their overall surface area. This method is less appropriate for management systems that involve regular additions of manure to existing heaps (e.g. daily, twice weekly) where there would be a continual need for sheet removal and replacement.

Likely Uptake: Low-moderate. *Note*: In NVZs it is mandatory to cover field heaps of layer manure with an impermeable sheet.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Indoor Pigs	Poultry	Costs based on provision of plastic sheeting and additional management time.
Annual	150	150	250	700	1,00	500	

Effectiveness:

N: NH_3 emissions have been shown to be reduced by up to 90% (mean reduction *c*.60%) by covering solid manure heaps with an impermeable sheet, however, N_2O emissions are likely to be increased during storage. NO_3 (plus ammonium and nitrite) leaching losses and associated indirect N_2O emissions would be reduced through lower leachate losses. Overall, NO_3 losses and NH_3 emissions would be decreased (i.e. the emission reduction during covering would be greater than increases following land spreading). Effects on the balance of N_2O emissions at the farm scale are uncertain. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

P: Losses would be reduced as less leachate would be produced.

FIOs and BOD: Losses would be reduced.

Other Pollutants: CH_4 emissions would be increased due to the greater propensity of anaerobic conditions under the sheeting. CO_2 emissions would increase by a very small amount as a result of heap covering activities. Odour emissions may be increased at heap break-out as a result of anaerobic heap storage conditions.

Key references:

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Chadwick, D. R. (2005). Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. *Atmospheric Environment,* 39, 787-799.

Chadwick, D.R., Matthews, R.A., Nicholson, R.J., Chambers, B.J. and Boyles, L.O. (2002). Management practices to reduce ammonia emissions from pig and cattle manure stores. In:

Proceedings of the 10th International Conference of the FAO RAMIRAN Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (Eds. J. Venglovsky and G. Greserova), pp.219-223.

Sagoo, E., Williams, J.R., Chambers, B.J., Boyles, L., Matthews, R. and Chadwick, D.R. (2004). Integrated management practices to minimise losses and maximise crop nitrogen value of broiler litter. In: *Proceedings of the 11th International Conference of the FAO RAMIRAN Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture* (Eds. Bernal, M.P., Moral, R., Clemente, R. and Paredes, C.), Vol. 1, pp.249-252.

Defra project WA0716 - Management techniques to reduce ammonia emissions from solid manures.

Method 63 – Use liquid/solid manure separation techniques

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	(↑↓)	(↑↓)	~	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	×	×	×	×	✓	×	×	×

Description: Use a separator to remove the suspended solids from slurry. This typically results in a 5-10% reduction in the volume of pig slurry and a 15-20% reduction in the volume of cattle slurry that needs to be stored and spread (Defra/EA, 2008).

Rationale: Separating the suspended solids from slurry means that the two manure streams can be handled separately. The solid fraction can be stored on a concrete pad or in a field heap, while the liquid fraction can be stored and transported/pumped to fields for land application. Separation enables greater flexibility in manure management and application timing.

Mechanism for action: Centrifuge, screw and drum separators reduce the amount of liquid manure to store; with the solid and liquid fractions being managed separately thereafter.

Potential for applying the method: This method is particularly applicable to farms with slurry that have outlying fields (to which slurry is rarely applied) and in helping farmers comply with the 250 kg/ha total N field limit in NVZs and as recommended in the Code of Good Agricultural Practice.

Practicability: The method usually involves a change in farm infrastructure, in addition to the cost of equipment purchase and maintenance etc. In some parts of England and Wales, capital grants are available for the purchase of slurry separators and associated infrastructure.

Likely uptake: Moderate, but could be high on large livestock farms to improve the logistics of slurry management.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Indoor Pigs	Costs based on the purchase of a slurry separator and provision of a concrete pad to store the solids, and are amortised.
Annual	2,600	4,600	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small (<2%) amount, as there is less slurry to be handled and hence there is greater flexibility in application timing, and associated indirect N_2O emissions. The overall effect on NH_3 and N_2O emissions at the farm scale is uncertain.

P: Losses are likely to be reduced by a small amount due to improved logistics of manure management.

FIOs and BOD: Losses are likely to be reduced.

Other Pollutants: CO_2 emissions would be increased by a small amount through operation of the separation equipment.

Key references:

Defra (2009). *A Code of Good Agricultural Practice for Farmers, Growers and Land Managers*. The Stationery Office, Norwich, ISBN 978-0-11-243284-5.

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Defra project WA0511 - An innovative approach to the treatment of farm effluent.

Defra project WA0507 - Quantifying factors which affect the fate of BOD from land applied wastes.

Method 64 – Use poultry litter additives

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	↓	~	~	↓	↓↓	↑	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	×	×	×	✓	×

Description: Add aluminium sulphate (Alum) to poultry litter during housing to reduce the pH of the litter; this will precipitate soluble P and reduce NH_3 emissions.

Rationale: Poultry litter contains 'high' concentrations of P and readily available (uric-acid and ammonium) N. Research has shown that P concentrations in surface runoff are closely related to the soluble P content of the manure. Alum additions to poultry litter precipitate P into a form that is not water-soluble. Also, Alum additions reduce NH_3 emissions from poultry litter which can result in heavier birds, better feed conversion efficiency and lower mortality.

Mechanism for action: Alum is applied to poultry litter at a rate equivalent to 5-10% by weight. For typical broiler operations growing 6 week-old birds, this is equivalent to adding 50-90 g Alum per bird. Aluminium (in Alum) reacts with P to form insoluble aluminium phosphate which is far less susceptible to soluble P loss in runoff. The reduction in NH_3 emissions is due to the acidity produced when Alum is added to the litter; the reduction in litter pH also causes pathogen numbers to decrease.

Potential for applying the method: This method is potentially applicable to all poultry operations that have 'dry' litter (e.g. broilers, breeders and turkeys).

Practicability: The method involves the application of Alum to new litter between each flock of birds. Alum (coarse powder/granules) can be applied using a range of 'small' fertiliser spreaders or litter 'de-caking' machines. To ensure that the birds do not consume the granules of Alum, it is best to incorporate the product into the litter.

Likely uptake: Low, due to costs and practicalities of application.

Costs:

Total *cost* for farm system (£/farm)	Poultry	Costs based on Alum application to litter.
Annual	1,800	

Effectiveness:

N: NH_3 emission reductions of around 70% have been reported from housing; and are also likely to be reduced during storage and following land spreading, as a result of the low litter pH. However, as a result of the higher readily available N content of the poultry litter NO_3 (plus ammonium and nitrite) leaching losses would be increased by a small amount (up to 20% of total N applied) and direct and indirect N_2O emissions following land spreading. *Overall* manure N use efficiency would be increased and manufacture N inputs reduced.

P: Soluble P losses in surface runoff have been shown to be reduced by up to 80% (in the short-term).

FIOs: FIO losses would be reduced as a result of the low litter pH.

Other pollutants: CO_2 emissions would be increased by a very small amount through Alum management. Impacts on other pollutants are likely to be minimal.

Key references:

Moore, P.A., Jr, Daniel, T.C. and Edwards, D.R. (2000). Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminium sulfate. *Journal of Environmental Quality,* 29, 37-49.

Shreve, B.R., Moore, P.A., Daniel, T.C., Edwards, D.R. and Miller, D.M. (1995). Reduction of phosphorus runoff from field-applied poultry litter using chemical amendments. *Journal of Environmental Quality,* 24, 106-111.

Method 65 – Change from a slurry to solid manure handling system

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓↓	↓↓	↓	↓↓	~	↓	↓	↓↓	(↑)	↓	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✗	✗	✗	✗	✓	✗	✗	✗

Description: Change from a system where the manure from housed animals is collected as a liquid (i.e. slurry) to one where animals are kept on bedding (e.g. straw) to produce solid manure.

Rationale: Solid manures are more easily stored than slurries and present less risk of pollutant loss during and following land spreading. Straw use also encourages bacterial immobilisation of readily available nitrogen, resulting in a lower potential for NH_3 emissions during housing, storage and following land spreading

Mechanism of action: Sufficient bedding is provided in animal housing to soak up the liquid portion of excreta to produce a solid manure that can be stacked and does not flow under gravity. Manure is generally allowed to accumulate in the house throughout the production cycle and is generally followed by storage in field heaps or on an impermeable base and then spreading to land. FIOs decline during storage as a result of elevated heap temperatures. ‘Fresh’ FYM typically contains 20-25% of its total N content as readily available N compared with *c.*45% for cattle slurry and *c.*70% for pig slurry. Also, as a result of their higher dry matter content, solid manures can be spread on fields with a much lower risk of nutrients and FIOs entering watercourses in surface runoff or via field drains.

Potential for applying the method: This method is applicable to cattle/pig farms with housed stock that currently handle all or part of their manure as slurry. It is not applicable to sheep or poultry units as these do not produce slurry.

Practicability: Solid manures require a source of suitable bedding materials and are less-suited to regions where little straw is produced (e.g. southwest England and Wales). There will be additional labour requirements associated with managing straw in the animal house and handling FYM. Also, some buildings may not be suitable for conversion to a solid manure system.

Likely Uptake: Low, due to the high costs of building conversion and cost/limited availability of straw.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Indoor Pigs	Costs based on changing livestock buildings to a straw management system, purchase of straw and additional manure management activities, and are amortised.
Annual	15,000	73,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 50% and direct and indirect N_2O emissions, and NH_3 emissions at land spreading would also be reduced; as a result of the lower readily available N content of FYM. NH_3 emissions would be reduced during housing and storage; although there is some evidence of higher NH_3 emissions from FYM based pig housing than from slurry based slatted-floor housing. N_2O emissions would be increased during FYM storage and reduced at land spreading; on balance N_2O emissions would (probably) be increased.

P: Soluble and particulate P losses would be reduced because of lower runoff risks.

FIOs and BOD: Losses would be reduced as a result of FIO die-off and BOD reductions during solid manure storage.

Other Pollutants: CH_4 emissions would be lower from solid manure systems. CO_2 emissions would be increased by additional manure handling activities. Odour emissions would be lower.

Key references:

Chambers, B.J., Williams, J.R., Cooke, S.D., Kay, R.M., Chadwick, D.R. and Balsdon, S.L. (2003). Ammonia losses from contrasting cattle and pig manure management systems. In: *Agriculture, Waste and the Environment* (Eds. I. McTaggart and L. Gairns), The Scottish Agricultural College, pp.19-25.

Defra project CC0234 - Nitrous oxide emissions from slurry-based and straw-based animal production systems.

Defra project IS0214 - New integrated dairy production systems: specification, practical feasibility and ways of implementation.

Defra project WA0632 - Ammonia fluxes within solid and liquid manure management systems.

Defra project WT0706 - Benefits and pollution swapping: cross-cutting issues for Catchment Sensitive Farming Policy.

Method 66 – Change from a solid manure to slurry handling system

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑↑	↑↑	↑↑	↑	↑↑	~	↑	↑	↑↑	(↓)	↑	↓

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✓	✗	✗	✗

Description: Change from a system where the manure from housed animals is collected as a solid to one where animals are kept on a liquid (i.e. slurry) based system.

Rationale: Slurry-based systems have a greater risk of pollutant losses during and following land spreading. However, solid manures contain both aerobic (and anaerobic) micro-sites where NH_4-N can be nitrified to NO_3-N, providing a source of NO_3 for N_2O emission (by denitrification). This can occur as the bedding material builds up in the animal house, and particularly once the bedding has been removed from the building for storage prior to land spreading. Slurry, on the other hand, is anaerobic (until the time it is spread onto land) and there is little or no N_2O emission from slurry-based buildings/stores.

Mechanism of action: Converting from a solid manure system to one that is slurry-based gives little or no possibility for slurry NH_4-N to be converted into NO_3, until it is spread onto land. Hence, N_2O emissions from housing and storage are lower from slurry-based systems than solid manure systems.

Potential for applying the method: This method is potentially applicable to those farms with housed stock that currently handle all or part of their manure as solid manure.

Practicability: Slurry-based systems will require storage facilities that a farmer would not necessarily have required for the storage of solid manure (e.g. a circular store, lagoon etc.). Pumps and slurry spreading equipment would be required, but less energy would be required to handle and spread slurry than solid manure. Also, existing building structures would need to be changed, with slatted flooring and slurry collection pits or new buildings constructed.

Likely Uptake: Low, due to the high costs of conversion and slurry storage provision. Additionally, changing to a slurry system is unlikely if the farm is located within an NVZ, where manure management regulations are much stricter for slurry than solid manures.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Indoor Pigs	Costs based on installation of cubicles and construction of a slurry storage tank, and are amortised.
Annual	14,000	3,000	3,500	5,500	27,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be increased by up to 50% and direct and indirect N_2O emissions, and NH_3 emissions at land spreading would also be reduced; as a result of the higher readily available N content of slurry. NH_3 emissions would be increased during housing and storage; although there is some evidence of lower NH_3 emissions from slurry based slatted-floor housing (compared with straw bedding). N_2O emissions would be reduced during slurry storage and increased at land spreading; on balance N_2O emissions would (probably) be reduced.

P: Soluble and particulate P losses would be increased because of higher runoff risks.

FIOs and BOD: Losses would be increased as a result of lower FIO die-off rates and BOD reductions in stored slurry.

Other Pollutants: CH_4 emissions would be increased from slurry compared with solid manure storage. CO_2 emissions would be reduced through manure management as slurry. Odour emissions would be higher.

Key references:

Chambers, B. J., Williams, J. R., Cooke, S. D., Kay, R. M., Chadwick, D. R. and Balsdon, S. L. (2003). Ammonia losses from contrasting cattle and pig manure systems. In: *Agriculture, Waste and the Environment,* (Eds. I. McTaggart and L. Gairns), The Scottish Agricultural College, pp.19-25

Del Prado, A. and D. Scholefield. (2008). Use of SIMSDAIRY modelling framework system to compare the scope on the sustainability of a dairy farm of animal and plant genetic-based improvements with management-based changes. *Journal of Agricultural Science,* 146, 1-17.

Defra project IS0214 - New integrated dairy production systems: specification, practical feasibility and ways of implementation.

Defra project WA0632 - Ammonia fluxes within solid and liquid manure management systems.

Defra project WA0646 - Fate of N following land application of solid and liquid pig manures.

Defra project WT0706 - Benefits and pollution swapping: cross-cutting issues for Catchment Sensitive Farming Policy.

Method 67 – Manure Spreader Calibration

Direction of change for target pollutants.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	~	~	~	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Determine the actual rate and evenness of manure (slurry and solid manure) applied by a spreader, and adjust it to obtain the desired agronomic rate.

Rationale: The even application of manure ensures that all parts of the field receive similar amounts of total and crop available nutrients.

Mechanism for action: The uneven spreading of manure can result in a variable supply of nutrients to the crop that is difficult to take into account as part of the farm nutrient management plan; so farmers tend to fertiliser to meet crop nutrient needs on under-applied areas. Over application of N results in higher post-harvest soil mineral N levels and greater potential for NO_3 leaching losses over-winter. Runoff risks would also be reduced.

Potential for applying the method: This method is applicable to all farms where manure is applied.

Practicability: Spreader calibration needs (ideally) to be repeated whenever there is a significant change in manure characteristics, or when a different application rate is used.

Likely uptake: Moderate

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on annual calibration and associated management time.
Annual	250	250	200	300	350	350	100	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses and associated indirect N_2O emissions would be reduced by a small (<5%) amount. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

P: Losses would be reduced by a small amount from slurry applications.

Other pollutants: Impacts on other pollutants are likely to be minimal.

Method 68 – Do not apply manure to high-risk areas

Direction of change for target pollutants where manure is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	~	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	×	×	✓

Description: Do not apply manure to field areas where there is a high-risk of direct loss to watercourses. For example, directly adjacent to a watercourse, borehole or road culvert, to shallow soils over fissured rock or widely cracked soils over field drains, to areas with a dense network of open (surface) drains, spring lines or wet depressions (flushes).

Rationale: These areas have a high-risk of rapid transport of manure-borne pollutants to watercourses, so manure applications (particularly of slurry) should be avoided wherever possible.

Mechanism of action: The method applies to areas where there is a high degree of hydrological connectivity between the field and watercourse; avoiding applications to such areas reduces the risk of pollutant transfer. The Code of Good Agricultural Practice advises that slurry and solid manures should not be spread within 10 m of a watercourse or within at least 50 m of a spring, well or borehole (used to supply water for human consumption or use in farm dairies). And in NVZs these rules are mandatory.

Potential for applying the method: This method is applicable to all farms applying manure, where there is a high degree of hydrological connectivity between the field and watercourse; these situations are most likely to be present in the wetter part of England (i.e. the west and south-west) and Wales.

Practicability: Although most hydrologically well-connected areas are likely to be easily identified, some old, but still functioning, drainage networks may not be known to the farmer (e.g. open surface drains, wet drained depressions, spring lines).

Likely Uptake: Moderate to high.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on the additional time needed to plan manure management activities to avoid high-risk areas.
Annual	130	130	100	150	180	180	30	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses and indirect and direct N_2O emissions would be reduced by a small (<1%) amount.

P: Soluble and particulate P losses would be reduced by a small (<2%) amount.

FIOs and BOD: Losses would be reduced by a small amount.

Other Pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Defra (2009). *A Code of Good Agricultural Practice for Farmers, Growers and Land Managers*. The Stationery Office, Norwich ISBN 978-0-11-243284-5.

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Defra project NT1835 - The effects of manure application to land on N loss pathways to air and water.

Method 69 – Do not spread slurry or poultry manure at high-risk times

Direction of change for target pollutants were manure is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓↓	↓↓	↓↓	↓↓	~	↓	↓	↑	↓	↑	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	×	×	✓	✓	×	×	×	×

Description:

- Do not apply slurry or poultry manure to fields at times when there is a high-risk of surface runoff e.g. in winter when soils are ‘wet’ or frozen hard, or when heavy rain is expected in the next few days.
- Do not apply slurry or poultry manure to fields at times when there is a high-risk of rapid percolation to field drains e.g. in winter and spring when soils are ‘wet’.
- Do not apply slurry or poultry manure to fields late in the growing season (i.e. autumn/early winter) when there is no crop to utilise the added N.

Rationale: Slurries and poultry manures have ‘high’ readily available N contents (>30% of total N). Avoiding the application of these materials at times when surface runoff or rapid preferential flow to field drains is likely to occur reduces water pollution risks. Also, avoiding application in autumn/early winter will help to reduce over-winter NO_3 leaching losses.

Mechanism of action: The method reduces the likelihood of recently applied slurry/poultry manure causing water pollution, via surface runoff or preferential flow in soil cracks to field drains. Also, slurry/ poultry manure applications in autumn/early winter add readily available N to the soil at a time when there is little N uptake by crops and will increase over-winter NO_3 leaching losses, particularly from nitrate ‘leaky’ sandy and shallow soils. Applications later in winter/spring present less of a risk, as there is less opportunity for NO_3 to be leached before crop growth commences.

Potential for applying the method: All farms producing (or importing) slurry and poultry manure. High-risk times will be most frequent in high rainfall areas, on sloping land and where soils are artificially drained (there are around 6 million hectares of drained soils in England and Wales).

Practicability: The method will be most applicable to farms that have sufficient slurry storage capacity to allow a choice of land application timing. However, even where storage is adequate for normal conditions, exceptional weather (and/or poor planning) can create a situation where stores are full during a high-risk period, so that land spreading is the only option.

Likely Uptake: Moderate to high.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Comb Crops	Comb/ Roots	Costs based on additional time to plan manure management activities.
Annual	130	180	180	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by up to 20% of total manure N applied and associated indirect N_2O emissions. However, NH_3 emissions would be increased by a small amount, as a result of more slurry being applied to dry (grassland) soils in summer. *Overall* manure N use efficiency would be increased and manufactured fertiliser N use reduced.

P: Soluble/particulate P losses would be reduced by up to 50%.

FIOs and BOD: Losses would be reduced as a result of lower runoff risks.

Other pollutants: CH_4 emissions would be increased by a small amount through the longer duration of storage. Impacts on other pollutant losses are likely to be minimal.

Key references:

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Withers, P.J.A., Davidson, I.H. and Roy, R.H. (2000). Prospects for controlling non-point phosphorus losses to water: A UK perspective. *Journal of Environmental Quality*, 29, 167-175.

Lord, E.I., Shepherd, M.A., Silgram, M, Goodlass, G., Gooday, R, Anthony, S.G., Davison, P. and Hodgkinson, R. (2007). *Investigating the Effectiveness of NVZ Action Programme Measures: Development of a Strategy for England.* Report for Defra Project NIT18.

Thorman, R. E., Sagoo, E., Williams, J. R., Chambers, B. J., Chadwick, D. R., Laws, J.A. and Yamulki, S. (2007). The effect of slurry application timings on direct and indirect N_2O emissions from free draining grassland soils. In. *Proceedings of the 15th Nitrogen Workshop*, Spain, pp. 297-299.
Defra project ES0106 - Developing integrated land use and manure management systems to control diffuse nutrient loss from drained clay soils: BRIMSTONE-*NPS*.
Defra project ES0115 - Optimising slurry application timings to minimise nitrogen losses: OPTI-*N*.

Method 70 – Use slurry band spreading application techniques

Direction of change for target pollutants where slurry is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓	(↑)	~	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✗	✗	✗	✗	✗

Description: Apply slurry to land in a series of narrow bands (typically 5 cm in width at a spacing of 20-30 cm). For applications with *trailing hose* equipment, the slurry is delivered via hoses just above the soil surface. For applications with *trailing shoe* equipment, slurry is delivered just behind a forward facing ‘shoe’, which ensures that the slurry is delivered directly to the soil surface below the grass sward/crop canopy.

Rationale: NH_3 volatilisation occurs from the surface of the applied slurry. Reducing the overall surface area of slurry, by application in narrow bands, will lead to a reduction in NH_3 emissions (provided that slurry infiltration into the soil is not delayed by the increased hydraulic loading rate on the slurry bands compared with broadcast spreading). In addition, if slurry is placed beneath the crop canopy, the canopy will also provide a physical barrier to reduce the rate of NH_3 loss.

Mechanism of action: *Trailing hose* – slurry is placed in narrow bands on the soil surface, via trailing hoses. As NH_3 volatilisation occurs from the slurry surface, applying the same volume of slurry in narrow bands rather than as an overall (broadcast) surface cover, will reduce the surface area to volume ratio of the applied slurry, reducing the area from which emission can occur. However, band spreading also increases the hydraulic loading rate per unit area, which can on some occasions (usually for high dry matter content slurries) impede infiltration into the soil. Also, for taller crops slurry will be delivered below the canopy, which will reduce air movement and temperatures at the emitting surface, thereby reducing NH_3 emissions.

Trailing shoe – slurry is placed in narrow bands on the soil surface, with a reduced surface area and increased hydraulic loadings as for the trailing hose above. Where a crop canopy is present, reduced air movement and temperatures at the soil surface, will also reduce NH_3 emissions.

Potential for applying the method: This method is applicable for all slurry applications to grassland (for which the trailing shoe is designed) and arable land (for which the trailing hose is designed). Applying slurry beneath the crop canopy (grassland or arable) avoids contamination of the crop with slurry and reduces odour emissions. For grassland, this reduces the required period between slurry application and grazing or silage harvest, extending the window of opportunity for slurry application. For arable crops, this extends the window for slurry application later into the spring when crop height would normally exclude conventional surface broadcast slurry application (because of crop damage and contamination risks). Trailing hose and trailing shoe equipment also deliver more uniform slurry applications, in comparison with conventional broadcast equipment which can be affected by wind and relies on the even matching of lapped spreading widths.

Practicability: Band spreading is generally a slower operation (with lower application rates) than conventional surface broadcast slurry application, so there may be some issues with labour availability. Many trailing hose slurry applicators have a boom width of less than 24m (although 24m booms are available), so for combinable crops with greater tramline spacings than the applicator boom width, slurry application will require travelling on the crop between tramlines, which may result in some crop damage (depending on growth stage at the time of application). On sloping land, the higher centre of gravity and additional width of some machines can increase the risk of ‘tipping over’.

Likely Uptake: Moderate, due to investment cost of new machines; although ‘high’ fertiliser N prices are encouraging increased use, particularly via contractors.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Costs based on additional contractor charges (and do not take into account improved crop N recovery).
Annual	1,500	400	250	1,700	

Effectiveness:

N: NH_3 reduction efficiencies for slurry spreading are typically 30% for trailing hose and trailing shoe equipment when the grass is short, and 60% for trailing shoe equipment when the grass is long (>10 cm) compared with broadcast application; although reductions can vary from 0-90%. Reducing NH_3 emissions from applied slurry will increase the potential for NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions. *Overall* manure N use efficiency would be increased and manufactured fertiliser N use reduced.

Other Pollutants: CO_2 emissions would be increased by a small amount. Odour emissions would be reduced. Impacts on other pollutants are likely to be minimal.

Key references:

Misselbrook, T. H., Smith, K. A., Johnson, R. A. and Pain, B. F. (2002). Slurry application techniques to reduce ammonia emissions: Results of some UK field-scale experiments. *Biosystems Engineering,* 81, 313-321.

Smith, K. A., Jackson, D. R., Misselbrook, T. H., Pain, B. F. and Johnson, R. A. (2000). Reduction of ammonia emission by slurry application techniques. *Journal of Agricultural Engineering Research,* 77, 277-287.

Williams, J.R., Chambers, B.J., Smith, K.A., Misselbrook, T.H. and Chadwick, D.R. (2000). Integration of farm manure nitrogen supply within commercial farming systems. In: *Proceedings of the Ninth International Conference of the FAO ESCORENA Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture: Technology Transfer* - RAMIRAN 2000 (Ed. F. Sangiorgi), University of Milan, pp.263-268.

Defra project ES0115 - Optimising slurry application timings to minimise nitrogen losses: OPTI-*N*.

Defra project CC0254 - Nitrous oxide from slurry applied to grass.

Defra project WA0637 - Denitrification and nitrous oxide emissions following new slurry application techniques for reducing ammonia losses.

Defra project KT0105 - MANure Nutrient Evaluation Routine. MANNER-*NPK*.

Method 71 – Use slurry injection application techniques

Direction of change for target pollutants where slurry is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	~	~	~	~	~	↓↓↓	(↑)	~	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	✓	×	×	×	×	×

Description: Deliver slurry to the soil in shallow surface slots (5-10 cm depth, at 20-25 cm spacing) which are cut by preceding discs, or much deeper into the soil (*c.*25 cm depth) where slurry placement is behind a tine.

Rationale: NH_3 volatilisation occurs from the surface of applied slurry. Reducing (for open slot shallow injection) or eliminating (for closed slot deep injection) the surface area of applied slurry reduces NH_3 emissions.

Mechanism of action: Placing slurry in narrow surface slots, via shallow injection, greatly reduces the exposed slurry surface area. Placing slurry deeper into the soil behind cultivation tines, as with deep injection, eliminates the exposed slurry surface area. NH_4-N in the slurry placed in the soil, will also be fixed on to clay particles, further reducing the potential for NH_3 emission.

Potential for applying the method: Shallow injection is most suited to grassland, where field slopes and/or stoniness are not limiting (estimated to rule out *c.*30% of agricultural land), and on arable land prior to crop establishment. Deep injection is most suited to arable land prior to crop establishment; current deep injector designs are generally not suited to application to growing crops, where crop damage can be great. Slurry injection will reduce crop contamination and odour emissions, and can (to some extent) increase the window of spreading opportunity compared with surface broadcast application. Also, slurry is applied much more uniformly across the entire application width in comparison with conventional broadcast equipment which can be affected by wind and relies on the even matching of lapped spreading widths.

Practicability: Work rates are slower (particularly for deep injection) than for conventional surface broadcast application. Also, injection equipment has a ‘high’ draught force, so large tractors are required (particularly for deep injection) and under hot and dry conditions can result in significant grassland sward damage. Shallow injection (particularly of dilute slurries) on sloping land can result in runoff along the injection slots. With deep injection, it is important to avoid slurry application directly into gravel backfill over field drains.

Likely Uptake: Moderate, due to investment costs of new machinery; although ‘high’ fertiliser N prices are encouraging increased use, particularly via contractors.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Costs based on additional contractor charges for shallow injection (and do not take into account improved crop N recovery).
Annual	2,200	600	400	2,500	

Effectiveness:

N: Deep injection would typically achieve >90% reduction and shallow injection around a 70% reduction in NH_3 emissions compared with surface broadcast application. Reducing NH_3 emissions from applied slurry will increase the potential for NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions. *Overall* crop N use efficiency would be increased and manufactured fertiliser N use reduced.

Other Pollutants: CO_2 emissions would be increased by a small amount. Odour emissions would be reduced. Impacts on other pollutants are likely to be minimal.

Key references:

Misselbrook, T. H., Smith, K. A., Johnson, R. A. and Pain, B. F. (2002). Slurry application techniques to reduce ammonia emissions: Results of some UK field-scale experiments. *Biosystems Engineering,* 81, 313-321.

Smith, K. A., Jackson, D. R., Misselbrook, T. H., Pain, B. F., and Johnson, R. A. (2000). Reduction of ammonia emission by slurry application techniques. *Journal of Agricultural Engineering Research,* 77, 277-287.

Williams, J.R., Chambers, B.J., Smith, K.A., Misselbrook, T.H. and Chadwick, D.R. (2000). Integration of farm manure nitrogen supply within commercial farming systems. In: *Proceedings of the Ninth International Conference of the FAO ESCORENA Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture: Technology Transfer* - RAMIRAN 2000 (Ed. F. Sangiorgi), University of Milan, pp.263-268.
Defra project CC0254 - Nitrous oxide from slurry applied to grass.
Defra project ES0115 - Optimising slurry application timings to minimise nitrogen losses: OPTI-N.
Defra project WA0637 - Denitrification and nitrous oxide emissions following new slurry application techniques for reducing ammonia losses.
Defra project KT0105 – MANure Nutrient Evaluation Routine. MANNER-*NPK*.

Method 72 – Do not spread FYM to fields at high-risk times

Direction of change for target pollutants where FYM is applied.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	~	↓	↓	~	↓	~	~

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	×	×	×	×	×

Description: Avoid spreading (straw-based) FYM to fields at times when there is a high-risk of surface runoff or drainflow, for example, where rain falls shortly after applying FYM to 'wet' soils.

Rationale: There is a risk of pollution if solid manures are spread under conditions where heavy rain following application could transport nutrients and FIOs to surface water systems.

Mechanism of action: As FYM is stackable and has a lower moisture content than slurry, it will not add sufficient water to the soil to initiate surface runoff or preferential flow to field drains; pollutants will only be transported to watercourses when there is heavy rainfall following application. 'Fresh' FYM has a higher content of readily available N and FIOs, and generally presents a greater risk of pollution than 'old' FYM that has been stored for several months. High-risk times will be most frequent in winter when soils are 'wet', particularly in high rainfall areas.

Potential for applying the method: The method is applicable to all livestock farms producing (or importing) FYM. The risks of surface runoff are greatest on sloping land on medium/heavy soils and where soils are artificially drained.

Practicability: Provided that the farm has an FYM storage area or the FYM can be left in the animal house until spreading conditions improve, there are few limitations to adopting this method.

Likely Uptake: High

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Costs based on additional time needed to plan manure management activities.
Annual	130	130	100	150	150	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small (<5%) amount and associated indirect N_2O emissions. *Overall* crop N use efficiency would be increased (by a small amount) and manufactured fertiliser N use reduced.

P: Losses in runoff would be reduced by a small (up to 5%) amount.

FIOs and BOD: Losses would be reduced by a small amount.

Other Pollutants: Impact on other pollutants are likely to be minimal.

Key references:

Chambers, B.J., Lord, E.I., Nicholson, F.A. and Smith, K.A. (1999). Predicting nitrogen availability and losses following application of organic manures to arable land: MANNER. *Soil Use and Management,* 15, 137-143.

Chambers, B. J., K. A. Smith, and B. F. Pain. (2000). Strategies to encourage better use of nitrogen in animal manures. *Soil Use and Management*, 16, 157-161.

Defra project OC8906 - Nitrogen leaching risk from livestock manures.

Method 73 – Incorporate manure into the soil

Direction of change for target pollutants on the area where manure is soil incorporated.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↑	↑	↑	↓	↓	~	↓	↓	↓↓	(↑)	~	~

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	✓	✓	×	×	×	×

Description: Incorporate manure rapidly into the soil using a plough, discs or tines.

Rationale: The rapid soil incorporation of manure can reduce pollutant losses in runoff and also reduce the exposed surface area of manure from which NH_3 emissions can occur.

Mechanism of action: Incorporation of manure can reduce the detachment and entrainment of manure particles by increasing surface roughness, promoting infiltration and preventing the exposure of manure to the hydrological forces of raindrop impact, surface runoff and drainflow loss. The rapid soil incorporation of manure (e.g. within 6 hours of spreading for slurry and 24 hours for solid manures) also reduces NH_3 volatilisation by reducing exposure to the air. NH_3 emission reductions depend on the time period between manure application and soil incorporation, and also on the cultivation technique employed. There is a considerable decrease in the abatement efficiency achieved if soil incorporation is delayed; incorporation as soon as possible after application should be the aim.

Potential for applying the method: Applicable to tillage land crops and reseeded grassland.

Practicability: In most circumstances, this method can be carried out as part of normal field preparations, although there may be a need to reschedule field operations to synchronise manure spreading and rapid soil incorporation activities. Where contractors are carrying out the manure spreading, it will require a degree of co-ordination between the contractor and farmer. If the rapid cultivation policy damages soil structure, this may compromise crop yields and result in applied fertiliser and organic manure N being poorly utilised by crops, and increase the risks of NO_3 leaching over the next winter drainage period.

Likely Uptake: Moderate to high. The soil incorporation of slurry and poultry manure where applications are made to uncropped land, as soon as possible and within 24 hours at the latest, is a mandatory requirement in NVZs.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Costs based on an additional cultivation (and do not take into account improved crop N recovery).
Annual	350	250	1,700	7,000	6,000	

Effectiveness:

N: NH_3 emissions would be reduced by around 60% where soil incorporation by ploughing occurred 6 hours after slurry application, and around 40% where FYM and 70% where poultry manure was incorporated by ploughing after 24 hours. NO_3 (plus ammonium and nitrite) leaching losses (especially where the manure was applied in the autumn) would be increased and direct (probably) and indirect N_2O emissions. *Overall* manure N use efficiency would be increased and manufactured fertiliser N inputs reduced.

P: Losses in surface runoff would be reduced.

FIOs and BOD: FIO and BOD losses would be reduced.

Other Pollutants: Impacts on other pollutants are likely to be minimal.

Key references:

Huijsmans, J. F. M., and de Mol, R. M. (1999). A model for ammonia volatilization after surface application and subsequent incorporation of manure on arable land. *Journal of Agricultural Engineering Research,* 74, 73-82.

Webb, J., Anthony, S. G., and Yamulki, S. (2006). Validating the MAVIS model for optimizing incorporation of litter-based manures to reduce ammonia emissions. *Transactions of the Asabe,* 49, 1905-1913.

Defra project NT2001 - Improved manure management: nutrient demonstration farms.

Defra project NT2008 - Nitrogen value of solid manures: effect of contrasting manure management practices.
Defra project WA0716 - Management techniques to reduce ammonia emissions from solid manures.
Defra project KT0105 - MANure Nutrient Evaluation Routine. MANNER-*NPK*.

Method 74 – Transport manure to neighbouring farms

Direction of change for target pollutants on farm exporting manure.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓↓	↓↓	↓↓	↓↓	~	↓↓	↓↓	↓↓	↓↓	↓	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	×	×	×	×	✓	×	✓	×

Description: For farms in NVZs where livestock manure N loadings exceed 170 kg total N/ha each year organic manure N in excess of this limit needs to be transported to farms that do not have surplus N (or a grassland derogation applied for, stocking rates reduced etc). This situation is most likely on dairy and pig farms (usually as slurry), and poultry farms (i.e. layer manure and poultry litter).

Rationale: Where there is a surplus of nutrients, manures can be exported to neighbouring farmland with spare livestock manure N capacity. As a result, exporting farms are able to 'balance' nutrients inputs with the capacity of crops to utilise those nutrients.

Mechanism of action: Nutrients are removed and exported to neighbouring farmland. This reduces the nutrient load on the farm and thereby reduces the risk of diffuse pollution from that farm. The export of manure should also enable the remaining manure to be managed in a more integrated way i.e. there will be less pressure to spread manures during high-risk periods and to better time applications in relation to crop demand.

Potential for applying the method: The method is most likely to be applicable to dairy, indoor pig and poultry farms.

Practicability: The method is reasonably easy to implement where receiving farm holdings are in close proximity (e.g. within 5-20 km).

Likely Uptake: Low/moderate on dairy farms and moderate/high on pig/poultry farms within NVZs. Low outside NVZ areas.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Indoor Pigs	Poultry	Costs based on the need to transport 25% of dairy slurry and all pig slurry/poultry manure 5-10 km.
Annual	2,200	16,000	7,000	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced on the exporting farm (by up to 10% on the dairy farm and up to 50% of pig/poultry farms) and increased (to a lesser extent) on the receiving farm with capacity to accommodate the excess manure. NH_3 and direct and indirect N_2O emissions would be reduced on the exporting farm.

P: Losses would be reduced on the exporting farm.

FIOs and BOD: Losses would be reduced on the exporting farm.

Other Pollutants: CH_4 emissions would be reduced on the exporting farm. CO_2 emissions would be increased by a small amount as a result of manure transport. Odour emissions may be increased as a result of manure transport. Biosecurity issues need to be considered.

Key references:

Defra/EA (2008). *Guidance for Farmers in Nitrate Vulnerable Zones*. Defra leaflets PB12736 a to i.

Fealy, R. (2008). Energy use and nutrient values in relation to manure transport distances. Proceedings 642. *International Fertiliser Society*, York, UK.

Method 75 – Incinerate poultry litter for energy recovery

Direction of change for target pollutants on combinable/root crop farm receiving poultry litter.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓↓	↓↓	↓	↓	~	↓	↓	↓↓	↓↓	↓	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	✓	×	×	×	×

Description: Transport poultry litter to an incinerator where it is burnt for energy recovery.
Rationale: Manure nutrients and FIOs are removed from the farm as a source of diffuse pollution.
Mechanism of action: Exporting the manure from the farm removes the source of pollution, with the ash (generally) returned to other farmland as a P and K fertiliser, where there is a requirement for these nutrients.
Potential for applying the method: The method is only applicable to poultry litter and some ‘dry’ layer manures. The moisture content of straw-based FYM is too high for incineration.
Practicability: Applicability is dictated by the availability of suitable incineration facilities within an acceptable distance of broiler/turkey farms (generally <100 km).
Likely Uptake: Currently, *c*.30% of broiler and turkey litter is sent for incineration in England.
Costs:

Total *cost* for farm system (£/farm)	Comb/ Roots	Costs based on the need to replace poultry litter nutrients with manufactured fertiliser inputs.
Annual	4,500	

Effectiveness:
N: NO_3 (plus ammonium and nitrite) leaching losses and ammonia emissions would be reduced, and direct and indirect N_2O emissions.
P: Losses would be reduced.
FIOs and BOD: Losses would be reduced.
Other Pollutants: CO_2 emissions would be increased as a result of poultry litter transport (plus emissions during incineration), however, energy would be produced during incineration. CH_4 emissions would be reduced (by a small amount) as litter would not be stored before land spreading.

Method 76 – Fence off rivers and streams from livestock

Direction of change for target pollutants in grazed fields with streams.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	~	~	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✗	✗	✗	✗	✗	✗

Description: Erect stock-proof fences in grazing fields and on trackways adjoining rivers and streams.
Rationale: Trampling by livestock can erode river/stream banks and increase sediment inputs to watercourses. Livestock can also add pollutants directly by urinating and defecating into the water. Preventing access eliminates this source of pollution.
Mechanism of action: Livestock, particularly cattle, can cause severe damage to river and stream banks when attempting to gain access to drinking water. The vegetative cover is destroyed and the soil badly poached, leading to erosion of the bank and increased transport of soil particles and associated nutrients into watercourses. Livestock also add nutrients and FIOs by defecating and urinating directly into the water. Fencing to prevent bank access eliminates this source of pollution.
Potential for applying the method: This method is applicable to all farms with grazing livestock and river/stream banks. Benefits will be greatest on farms with large cattle or sheep numbers. The method is not applicable to outdoor pigs, as these are securely fenced and do not have direct access to rivers or streams.
Practicability: The method is less applicable to upland beef/sheep farms with extensive areas of rough grazing and considerable lengths of unfenced river/stream banks. There is likely to be a need to provide an alternative source of drinking water. This method will be most effective when combined with Method 77 – 'construct bridges for livestock crossing rivers/streams' (if applicable).
Likely Uptake: Moderate. There are capital grants available for fencing off streams and rivers in England Catchment Sensitive Farming Delivery Initiative (ECSFDI) priority catchments. The fencing of watercourses is also supported by Higher Level Scheme (HLS) funding in England and Tir Gofal funding in Wales.
Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Costs are based on provision of standard fencing and water troughs and are amortised.
Annual	2,000	1,000	1,300	2,000	

Effectiveness:
N: NO_3 (plus ammonium and nitrite) losses would be decreased by a small (<2%) amount.
P: Particulate/soluble P and associated sediment losses would be reduced by a small (up to 5%) amount.
FIOs and BOD: Losses would be reduced by a small (up to 5%) amount.
Other Pollutants: CO_2 emissions would be increased by a very small amount through fencing/water trough installation. Impacts on other pollutants are likely to be minimal.
Key references:
Defra project ES0126 - Integrated Catchment Management at Whittle Dene - Phase II.

Method 77 – Construct bridges for livestock crossing rivers/streams

Direction of change for target pollutants in grazed fields with river/stream crossings.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	↑	~	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	×	✓	✓	×	×	×	×	×	×

Description: Construct bridges to allow livestock and vehicles to cross rivers and streams without damaging the banks, and to prevent animals urinating and defecating directly into the water.

Rationale: Where livestock ford rivers and streams, they can erode banks, disturb the stream bed and increase inputs of sediment to watercourses. Stock can also add pollutants directly by urinating and defecating into the water. Provision of bridges removes the need for fording watercourses and eliminates this source of pollution.

Mechanism of action: Trampling by livestock and damage from wheeled traffic will cause sediment loss on either side of the fording position and stir up sediment on the river/stream bed. This will increase the transport of sediment and associated nutrients downstream; although this will be less of a problem where there is a coarse, stony river bed. Also, livestock may defecate and urinate directly into the watercourse, providing a direct input of nutrients and FIOs. Providing bridges to avoid the need for animals (and traffic) to enter the stream will eliminate this source of pollution.

Potential for applying the method: This method is applicable to all livestock farms where there are stream crossings without bridges, and particularly dairy farms where cows are typically moved between the fields and milking parlour twice a day. This method will be most effective when combined with Method 76 – ‘fence off rivers and streams from livestock’.

Practicability: There are few circumstances that would limit the adoption of this method, although it would be less practical on upland farms with extensive areas of rough grazing and many river/stream crossing points.

Likely Uptake: Moderate**.**

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Costs based on the construction of two bridges per farm and are amortised.
Annual	1,200	1,000	1,500	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) losses would be reduced by a small (<2%) amount. There would be a small increase in NH_3 emissions from urine deposition on the impermeable (bridge) surface.

P: Particulate/soluble P and associated sediment losses would be reduced by a small (up to 5%) amount.

FIOs and BOD: Losses would be reduced by a small (up to 5%) amount.

Other Pollutants: CO_2 emissions would be increased by a small amount through bridge construction.

Key references:

Defra project ES0126 - Integrated Catchment Management at Whittle Dene - Phase II.

Method 78 – Re-site gateways away from high-risk areas

Direction of change for target pollutants in fields with gates in high-risk areas.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	~	↓	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	✓	×	✓

Description: Move gateways located in high-risk surface runoff areas, such as at the bottom of a slope and near to a watercourse, to lower-risk areas on upper slopes.

Rationale: Many fields have gateways located at the bottom of a slope and near to a watercourse. Increased activity occurs around gateways, including trampling by livestock (particularly on dairy farms) and compaction by machinery. Repositioning the gateway would decrease the potential for sediment and associated nutrient (and FIOs from grazed grass fields) losses, by reducing hydrological connectivity.

Mechanism of action: A gateway at the bottom of a slope provides a break in the field boundary which might otherwise retain surface runoff within the field. In addition to the poaching and compaction that occurs around gateways, ruts from tractor wheelings and animal tracks tend to converge on these points and channel surface runoff to these positions. Re-siting gateways away from the lower boundary of fields lessens the risk of surface runoff transporting sediment, associated nutrients and FIOs out of sloping fields and directly into watercourses or onto roads etc.

Potential for applying the method: This method is applicable to all farming systems on sloping land, with gateways in high runoff risks, areas and is relatively easy to implement.

Practicability: Re-locating gates from high-risk to lower-risk areas should be practicable on most fields in sloping areas. Farmers may be reluctant to re-locate gateways, but if it improves opportunities for access, then it may be seen as advantageous, particularly in wet years. Practicability will be reduced where new tracks have to be constructed in addition to new gateways.

Likely Uptake: Low to moderate. There are capital grants available for moving and resurfacing gateways in England Catchment Sensitive Farming Delivery Initiative (ECSFDI) priority catchments.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Outdoor Pigs	Hort	Costs based on the relocation of gateways in approximately one third of fields and are amortised.
Annual	1,600	1,000	900	1,200	4,000	4,000	450	150	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses would be reduced by a small (<1%) amount and associated indirect and direct N_2O emissions.

P: Particulate/soluble P and associated sediment losses would be reduced by up to 10%.

FIOs and BOD: Losses would be reduced by a small (<1%) amount from grazed grassland fields.

Other Pollutants: CO_2 emissions would be increased by a small amount through gateway relocation. Impacts on other pollutants are likely to be minimal.

Method 79 – Farm track management

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓	↓	↓	↓	↓	~	↓	~	↑

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	✗	✗	✗	✓

Description:

- Create well-drained tracks with appropriate surfaces;
- Avoid routes with steep slopes;
- Improve track surfaces and repair any damage promptly;
- Provide good drainage and divert runoff to adjacent grassed areas, soakaways or swales;
- Avoid directing runoff towards bare soil, roads or watercourses.

Rationale: Farm tracks are used to transport vehicles and livestock on a regular basis (especially on dairy farms) and can become ‘rutted’ very quickly. On sloping land in wet conditions, these ruts form channels and that generate significant volumes of surface runoff. Also, waterlogged tracks can cause problems to livestock, including foot, mastitis and teat and udder damage. Improving track drainage and diverting surface runoff to adjacent grass, soakaways or swales can reduce the mobilisation and transport of pollutants.

Mechanism for action: Tracks can quickly become waterlogged in wet conditions. On sloping land, surface runoff can be generated mobilising sediment and manure-borne pollutants. Constructing tracks from appropriate materials can improve drainage and reduce runoff volumes. Cross drains and soakaways reduce the energy of overland flow, reduce pollutant mobilisation and increase the opportunity for the retention of mobilised pollutants. The location and route of tracks is also important; following contours and avoiding steep slopes can minimise concentrated flows and reduce the risk of track and adjacent field erosion.

Potential for applying the method: The method is applicable to all farms that have farm tracks and is most applicable to dairy farms on steeply sloping land where the animals are moved regularly.

Practicability: Track maintenance and repair requires time and investment. Changing track routes to avoid steep slopes or erodible soils is less likely to occur due to cost and land use implications.

Likely uptake: Moderate. There is a financial and welfare incentive to maintain and/or improve existing tracks. In England Catchment Sensitive Farming Delivery Initiative (ECSFDI) priority catchments, there are capital grants available for installing livestock and farm machinery tracks, cross drains, sediment traps and swales.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on installing sumps and maintaining silt traps, and are amortised.
Annual	200	200	150	200	200	250	80	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) losses and associated indirect N_2O emissions would be reduced by a very small (<1%) amount.

P: Particulate/soluble P and associated sediment losses would be reduced by a small (<2%) amount.

FIOs and BOD: Losses would be reduced by a small (<2%) amount.

Other Pollutants: CO_2 emissions would be increased by a very small amount through track management activities.

Key references:

Environment Agency (2008). *Best Farming Practices*. Environment Agency. 97pp.

Method 80 – Establish new hedges

Direction of change for target pollutants at the farm scale.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓↓	↓	↓↓	↓*	↓*	~	↓	~	↑

* Farms with livestock/manures.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✓	✓	✓	✓	✓	×	✓	×	✓

Description: Plant new hedges along fence lines and use them to break-up the hydrological connectivity of the landscape.

Rationale: Increasing the number of hedgerows can help to reduce sediment and associated nutrient losses by ‘trapping’ and lowering surface runoff volumes. Hedges can also help to protect soils from wind erosion.

Mechanism of action: Installing hedges reduces the slope length and helps to prevent the delivery of pollutants in surface runoff by reducing the force of flow. Hedges also act as ‘natural’ buffer strips and sediment traps, and enable separate parts of the landscape to be managed in different ways.

Potential for applying the method: This method is applicable to most farming systems, but is likely to be more applicable to the arable sector where hedgerows have been removed, particularly on erosion susceptible sandy and silty soils on sloping land.

Practicability: Planting hedges and making fields smaller, will increase the time required for field operations and may be resisted by some larger arable farms. On grassland farms it may help with stock management and provide useful shelter in summer. As laying hedges involves considerable time and investment on most farms it would be carried out over a number of years to fit in with farming operations. The method is compatible with Environmental Stewardship Schemes.

Likely Uptake: Low to moderate, as a result of time and cost implications.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing LFA	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Outdoor Pigs	Hort	Cost based on planting new hedges, installing new gateways and back fencing, and are amortised.
Annual	4,000	3,000	2,500	4,500	4,800	8,000	2,200	1,400	

Effectiveness:

N: NO_3 (plus ammonium and nitrite) leaching losses and direct and indirect N_2O emissions would be reduced by a small (<1%) amount; as a result of the land area (*c.*1%) being taken out of production.

P: Particulate/soluble P and associated sediment losses would be reduced by up to 20%.

FIOs and BOD: Losses would be reduced by a small amount (<1%) from grazed grassland fields.

Other pollutants: CO_2 emissions would be increased by a small amount through hedge planting activities etc.

Method 81 – Establish and maintain artificial wetlands

Direction of change for target pollutants on the farm area where runoff is intercepted by the wetland.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓	↓	↓	↓↓	↓	↓↓	↓↓↓*	↓↓↓*	~	↑	↑	↑

( ) Uncertain
*Runoff from dairy hardstandings

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✓	✓	✓	✓	✗	✗	✗	✓

Description: Construct (or establish) wetlands with fences and channels that will be sufficient to capture runoff and sediment from a field group of fields or farm hardstandings.
Rationale: Constructed wetlands can be used for the 'treatment' of lightly contaminated runoff from farm hardstanding areas and to intercept runoff water from a field or group of fields. They can trap sediment and through the retention of runoff, reduce nutrient and FIO loads in water exiting the wetland.
Mechanism of action: Wetlands act by intercepting pollutant delivery through providing a 'buffer zone' and can potentially clean up polluted water. They can be natural or artificial, permanent or temporary, with water that is static or slow flowing. Constructed wetlands can be either surface (overland) flow or subsurface (percolation) flow systems. A surface flow wetland is akin to a natural wetland; in the form of a reed bed, bog, wet grassland, wet woodland, sedimentation pond or lake. A subsurface flow wetland is generally a highly engineered, confined system of graded gravels and reeds. A range of biological, physical and chemical processes occur in the wetland environment, which can reduce nutrient and FIO concentrations in water that passes through the wetland.
Potential for applying the method: Wetlands can potentially be applied to all farming systems on medium/heavy soils with moderate to poor drainage, but are particularly suited to land where 'elevated' sediment and associated nutrient losses occur. They are not effective on free-draining soils, where drainage water moves to groundwater. There will be a need to liaise with the Environment Agency (EA) regarding construction criteria etc.
Practicability: Wetlands can be difficult to construct and will inevitably involve the loss of some agricultural land. However, where they can be used to address a pollution problem they are likely to be reasonably acceptable to farmers. The outflow of water from artificial wetlands into a watercourse may require a discharge consent from the EA; there will also be a need to obtain EA approval if the wetland is being used to treat farm hardstandings runoff. Constructed subsurface flow systems require maintenance, due to the deposition of sediment, which can result in some sections becoming impermeable. Wetlands may also result in the re-mobilisation of pollutants and will need cleaning-out periodically as sediment levels etc. build-up.
Likely Uptake: Low, due to construction costs, loss of agricultural land and need for EA approval.
Costs:

Total *cost* for farm system (£/farm)	Dairy	Grazing Low	Mixed	Comb Crops	Comb/ Roots	Hort	Costs based on a reedbed for dairy steadings and field wetlands for arable land (occupying 0.25% of farm area) and are amortised.
Annual	200	100	1,000	2,200	2,400	300	

Effectiveness:
N: NO_3 (plus ammonium and nitrite) losses could be reduced by up to 20%. However, N_2O emissions may be increased from the wetland itself.
P: Particulate P and associated sediment losses could be reduced by up to 80% from arable fields draining to the wetland. Soluble P losses could be reduced by a small amount (up to 20%).
FIOs and BOD: Losses could be reduced by up to 90%.
Other Pollutants: CO_2 emissions would be increased due to wetland construction. CH_4 emissions are likely to increase, particularly where the wetlands are treating lightly contaminated runoff from hardstandings.

Key references:

Reay, D.S. and Paul, G. (2008). Novel quantification of methane emissions from a constructed wetland in the Scottish Borders. In, *Land Management in a Changing Environment*. Proceedings of the SAC and SEPA Biennial Conference, Edinburgh, 26-27 March 2008, pp.183-189.

Søvik, A.K., Augustin, J., Heikkinen, K., Huttunen, J.T., Necki, J.M., Karjalainen, S.M., Kløve, B., Liikanen, A., Mander, Ü., Puusinen, M., Teiter, S. and Wachniew, P. (2006). Emission of the greenhouse gases nitrous oxide and methane from constructed wetlands in Europe. *Journal of Environmental Quality,* 35, 2360-2373.

Defra project ES0132 - A review of 'soft engineering' techniques for on-farm bioremediation of diffuse and point sources of pollution.

Method 82 – Irrigate crops to achieve optimum yields

Direction of change for target pollutants on the area of irrigated crops.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
↓↓	↓	↓	↑	~	↑	~	~	~	(↓)	~	↑

( ) Uncertain.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
×	×	×	×	×	✓	×	×	×	✓

Description: Irrigate crops (potatoes, vegetables and soft fruit) to reduce soil moisture deficits at critical times during growth to optimise yields and nutrient uptakes.
Rationale: The supply of water at appropriate times during the growing season ensures optimal crop growth and nutrient uptake, and reduces the amount of NO_3 available for leaching over the following winter, as a result of restricted N uptake due to drought.
Mechanism for action: Irrigation scheduling is designed to maintain soil moisture at optimum levels at critical times in the growing season. Yields are optimised, such that more N is taken up by the crop and less NO_3 is available for leaching post-harvest.
Potential for applying the method: The method is most applicable to high value crops (e.g. potatoes, vegetable and soft fruit crops) in low rainfall areas *e.g.* sandy soils in eastern and central England.
Practicability: Irrigation supply requires either a constant source of water (extraction licence or mains) or a storage reservoir.
Likely uptake: Low, as water availability and the costs of implementing the required infrastructure can be high.
Costs:

Total *cost* for farm system (£/farm)	Comb/ Roots	Hort	Costs based on installation of a reservoir/borehole, irrigation equipment, licensing and application costs and are amortised. No account has been taken of increased crop yields and quality.
Annual	6,000	5,500	

Effectiveness:
N: NO_3 (plus ammonium and nitrite) leaching losses and associated indirect N_2O emissions would be reduced by around 40%. However, there is a potential for increase direct N_2O emissions as a result of ‘wet’ soil conditions through irrigation water application.
P: Particulate P and associated sediment losses could be increased on sloping sandy/silty soils by up to 20%.
Other pollutants: CO_2 emissions associated with reservoir construction/borehole installation and water application would be increased.
Key references:

Groves, S.J. and Bailey, R.J. (1997). The influence of sub-optimal irrigation and drought on crop yield, N uptake and risks of N leaching from sugar beet. *Soil Use and Management*, 13, 190-195.
Defra projects NT0110/NT1306/NT1807/NT1808 - Nitrate leaching: management practices in crop rotations.
Defra projects NT0201/NT1307 - To provide guidelines for improved nitrogen use on potatoes, oilseed rape & sugar beet.
Defra project NT1805 - Effects of crop rotation and management practice on nitrate leaching from a sandy soil.

Method 83 – Establish tree shelter belts around livestock housing and slurry storage facilities

Direction of change for target pollutants.

Nitrogen			Phosphorus		Sediment	BOD	FIOs	Ammonia	Nitrous Oxide	Methane	Carbon Dioxide
Nitrate	Nitrite	Ammonium	Part	Sol							
~	~	~	~	~	~	~	~	↓	~	~	~*

* Plus carbon storage in vegetation and soil.

Farm typologies applicable:

Dairy	Grazing LFA	Grazing Low	Mixed	Combinable Crops	Combinable Roots	In Pigs	Out Pigs	Poultry	Horticulture
✓	✗	✗	✗	✗	✗	✓	✗	✗	✗

Description: Plant tree shelter belts around livestock housing and slurry storage facilities.

Rationale: The tree shelter belt will disrupt air flows around the building or slurry storage facility, reducing NH_3 emission rates and will also directly re-capture a proportion of the emitted NH_3.

Mechanism of action: Planting tree shelter belts upwind and downwind of livestock housing or slurry storage facilities will reduce NH_3 emissions in two ways. Firstly, the shelter belt will result in a lower wind speed directly above and around the building or slurry store, and thereby will increase the time taken for emitted NH_3 to be transported away in the air stream. Secondly, the trees will re-capture a proportion of the emitted NH_3 both directly though cuticular uptake and also indirectly by increased deposition.

Potential for applying the method: This method could potentially be applied to all livestock housing facilities (where spare is available). The effectiveness of the method in reducing NH_3 emissions will depend on the height and canopy density of the shelter belt, and the prevailing environmental conditions.

Practicability: A shelter belt of sufficient height (to be effective) will take a number of years to establish.

Likely Uptake: Low-moderate, due to financial costs and land area loss.

Costs:

Total *cost* for farm system (£/farm)	Dairy	Indoor Pigs	Costs based on the establishment of a 30m deep shelter belt of trees around the perimeter of the livestock building/slurry store and are amortised (they assume no loss of crop production).
Annual	400	800	

Effectiveness:

N: NH_3 emission could be reduced by up to 10%.

Other Pollutants: Shelter belts can offer additional benefits including visual screening, enhanced biodiversity and carbon sequestration. However, there may be some disbenefits, including loss of the land from agricultural production, shading of adjacent farmland etc. Impacts on other pollutants are likely to be minimal.

Key references:

Dragosits, U., Theobald, M. R., Place, C. J., ApSimon, H. M. and Sutton, M. A. (2006). The potential for spatial planning at the landscape level to mitigate the effects of atmospheric ammonia deposition. *Environmental Science & Policy,* 9, 626-638.

Defra project WA0719 - Impact of vegetation and/or other on-farm features on net ammonia emissions from livestock farms.

APPENDIX I. DESCRIPTION OF THE FARM TYPOLOGIES

The Mitigation Methods – User Guide effectiveness and cost *estimates* were calculated for twelve defined farm typologies from which baseline pollutant losses were calculated (based on established baseline farm infrastructures and farm practices). The cost estimates and ranges of effectiveness of methods detailed in this Guide should therefore be considered with reference to the farm typology descriptions set out below.

Farm typology – Cropping and livestock numbers

The farm typologies were based on the nine 'Robust Farm Types' (RFTs) used by the Farm Business Survey and defined by the dominant source of revenue (MAFF, 1993). The farm typologies excluded 'Other' RFTs which define holdings that either do not fit in well with mainstream agriculture or are of limited economic importance.

The farm typology sizes (total arable crop and grassland areas) were based on the average farm areas given in the Farm Business Survey for 2006 (for England).
Note. The farms surveyed by the Farm Business Survey are generally larger than the average census farm, as the survey excludes minor holdings. The proportions of the land area occupied by each crop type and the stocking densities of each livestock type were derived for each farm type from the Defra June Agricultural Census for 2004. The crop areas and stock numbers were then 'benchmarked' so that the totals across all farms agreed with the published census data; this also accommodated the relatively small land area and livestock numbers on the 'Other' RFTs.

To ensure that the farm typologies had physically realistic crop rotations and livestock numbers, some adjustments were made to the average farm statistics. For example, very small numbers of pigs and poultry were removed from the 'Dairy' farm and the total numbers of cattle were adjusted to achieve a typical economic stocking rate. These adjustments were necessary to convert a statistical farm definition averaged across all surveyed farms of a type, into a more realistic and recognisable farm typology.

Tables A1 to A3 summarise the farm typology cropping rotations and livestock numbers.

Farm typology – Practices

Farm infrastructure and detailed practices within each farm typology were based on survey and research data where this was available, and on expert judgement.

The farm typologies include information on N and P excretion/production from livestock (Cottrill and Smith, 2010); the amount of excreta managed as manure (Webb *et al*., 2004; Misselbrook *et al*., 2007); livestock activity data (Webb *et al*., 2001; Farm Practice Survey data for 2001 (Scott *et al*., 2002) and 2004 (Defra, 2004b); hardstanding areas (Webb *et al*., 2001); wash water use (Laws and Chadwick, 2005); cultivation type and timing (Scott *et al*., 2002); average fertiliser application rates, with and without manure (Goodlass and Welch, 2005); the proportion of N fertiliser applied as urea (Goodlass and Welch, 2005); and the timing of fertiliser, manure and dirty water applications (Goodlass and Welch, 2005; Smith *et al*., 2000; 2001a; 2001b).

Table A1 Summary of cropping (ha) on each of the representative farm typologies.

Crops		**Farm Typologies**									
		Dairy	**Grazing – LFA**	**Grazing - Lowland**	**Mixed**	**Combinable Cropping**	**Roots Cropping**	**Indoor Pigs**	**Outdoor Pigs**	**Specialist Poultry**	**Horticulture**
Grassland (ha)	Permanent grassland	71	62	75	74	-	15	-	-	-	3
	< 5 year rotational grassland	24	5	16	22	-	-	-	18	-	-
	Rough grazing*	6	79	4	5	5	2	-	-	-	-
	Sub-total	**101**	**146**	**95**	**101**	**5**	**17**	**-**	**18**	**-**	**3**
Tillage land (ha)	Winter Wheat	2	-	0	15	102	65	-	-	-	0
	Winter Barley	0	-	4	10	16	9	-	-	-	0
	Spring Barley	3	-	1	8	11	8	-	-	-	0
	Maize	6	-	1	5	0	0	-	-	-	0
	Sugar Beet	0	-	0	0	0	25	-	-	-	0
	Oilseed Rape	0	-	0	8	31	0	-	-	-	0
	Potatoes	0	-	0	0	0	18	-	-	-	0
	Fodder Crops e.g. Stubble Turnips	2	-	0	2	0	0	-	-	-	0
	Other Crops e.g. Peas, Beans, Linseed etc	0	-	0	6	7	28	-	-	-	0
	Vegetables for Human Consumption	0	-	0	0	0	10	-	-	-	8
	Horticultural Crops e.g. Top Fruit etc	0	-	0	0	0	0	-	-	-	7
	Sub-total	**13**	**-**	**6**	**54**	**167**	**163**	**-**	**-**	**-**	**15**
Total (ha)		**114**	**146**	**101**	**155**	**172**	**180**	**-**	**18**	**-**	**18**

* or rough land/set-aside

Table A2. Summary of cattle and sheep numbers on each of the representative farm typologies (by stock type and age).

Livestock Categories		**Farm Typologies**									
		Dairy	**Grazing – LFA**	**Grazing - Lowland**	**Mixed**	**Combinable Cropping**	**Roots Cropping**	**Indoor Pigs**	**Outdoor Pigs**	**Specialist Poultry**	**Horticulture**
Cattle	Dairy Cows	110	-	-	31	-	-	-	-	-	-
	Dairy Heifers in Calf, >2 years	14	-	-	-	-	-	-	-	-	-
	Dairy Heifers in Calf, <2 years	14	-	-	-	-	-	-	-	-	-
	Beef Cows and Heifers	-	22	27	21	-	-	-	-	-	-
	Beef Heifers in Calf >2 Years	-	3	2	3	-	-	-	-	-	-
	Beef Heifers in Calf <2 Years	-	1	1	2	-	-	-	-	-	-
	Bulls	1	1	1	1	-	-	-	-	-	-
	Other Cattle, >2 Years	-	11	14	5	-	-	-	-	-	-
	Other Cattle, 1-2 Years	31	14	37	53	-	-	-	-	-	-
	Other Cattle, <1 Year	45	20	39	40	-	-	-	-	-	-
	Total	**215**	**72**	**121**	**156**	**-**	**-**	**-**	**-**	**-**	**-**
Sheep	Sheep	50	358	184	190	-	-	-	-	-	-
	Lambs, <1 Year	54	339	170	203	-	-	-	-	-	-
	Total	**104**	**697**	**354**	**393**	**-**	**-**	**-**	**-**	**-**	**-**

Table A3. Summary of pig and poultry numbers on each of the representative farm typologies (by stock type and age).

Livestock Categories		Farm Typologies									
		Dairy	Grazing – LFA	Grazing - Lowland	Mixed	Combinable Cropping	Roots Cropping	Indoor Pigs	Outdoor Pigs	Specialist Poultry	Horticulture
Pigs	Sows in Pig and Other Sows	-	-	-	18	-	-	159	294	-	-
	Gilts in Pig and Barren Sows	-	-	-	2	-	-	71	62	-	-
	Gilts Not Yet in Pig	-	-	-	9	-	-	133	78	-	-
	Boars	-	-	-	2	-	-	6	6	-	-
	Other Pigs >110kg	-	-	-	4	-	-	32	-	-	-
	Other Pigs 80-110kg	-	-	-	65	-	-	247	-	-	-
	Other Pigs 50-80kg	-	-	-	92	-	-	621	-	-	-
	Other Pigs 20-50kg	-	-	-	102	-	-	983	-	-	-
	Other Pigs <20kg	-	-	-	106	-	-	1,272	-	-	-
	Total	**-**	**-**	**-**	**400**	**-**	**-**	**3,524**	**440**	**-**	**-**
Poultry	Layers	-	-	-	252	-	-	-	-	14,709	-
	Pullet	-	-	-	60	-	-	-	-	4,191	-
	Broilers	-	-	-	928	-	-	-	-	55,772	-
	Turkeys	-	-	-	642	-	-	-	-	1,379	-
	Breeding Bird	-	-	-	358	-	-	-	-	2,602	-
	Ducks	-	-	-	365	-	-	-	-	2,704	-
	Total	**-**	**-**	**-**	**2,605**	**-**	**-**	**-**	**-**	**81,357**	**-**

Livestock N and P production

Cottrill and Smith (2010) estimated livestock N (and P) excretion/production to underpin implementation of the Nitrate Pollution Prevention Regulations 2008; with the N production values summarised in Defra/EA (2008). The proportions of manure spread direct from housing (or other minimal storage) and the amounts of manure handled as slurry or FYM were derived from NARSES (National Ammonia Reduction Strategy Evaluation System) outputs; Defra projects AM0101 and AC0102.

Manure stores and hardstandings

The type and size of manure stores was derived from the Farm Practice Surveys for 2001 (Scott *et al*., 2002) and 2004 (Defra, 2004b). The area of hardstandings was taken from Webb *et al.* (2001) and the amount of wash water used from Laws and Chadwick (2005).

Livestock and crop calendar

The proportion of time that animals spent in housing, gathering yards, the milking parlour or at grazing was estimated by month for each livestock type based on data in Misselbrook *et al*. (2007), Webb *et al*. (2001) and the Farm Practice Survey for 2001 (Scott *et al*., 2002). The winter housing period for grazed livestock was taken from Cottrill and Smith (2010). During the grazing season livestock were distributed across the farm with 30% of the grassland area cut twice for conservation, 30% cut once and 40% grazed throughout the season. Within the grazing typologies, sheep and lambs made use of rough grazing and fodder crops, as well as the permanent/temporary grassland areas. For arable (tillage) land, the type and timing of cultivations was taken from the Farm Practice Survey for 2001 (Scott *et al*., 2002); with drilling and harvest dates taken from Soffe (2003).

Fertiliser Practice

Nitrogen and phosphate fertiliser use was taken from *overall* use figures reported in the British Survey of Fertiliser Practice - BSFP (Goodlass and Welch, 2005), with application rates adjusted to account for livestock manure use (where appropriate). The type and timing of fertiliser applications was taken from a detailed analysis of BSFP returns for 2003, undertaken in support of Defra project NT2605 (Chadwick *et al*., 2005).

Manure Management

The farm typologies provide a detailed calendar of the amount of each manure type spread to each crop type. The volume of dirty water generated on hard standing areas and the dilution of slurry in open stores was also calculated. The total amounts of N remaining in manures post housing and storage losses was estimated using the figures provided by Cottrill and Smith (2010). The timing and location of manure spreading to land was based on data from Smith *et al*. (2000; 2001a; 2001b) and additional information from the British Survey of Fertiliser Practice on monthly timings (Goodlass and Welch, 2005). The method of manure spreading and delay to soil incorporation (where applicable) were based on NARSES (Webb and Misselbrook, 2004) outputs. The mass (or volume) of FYM and slurry applied to each crop in each month was back-calculated using the total amount of N applied and the ‘typical’ total N content of manures (kg/t or m^3) given in the “Fertiliser Recommendations booklet RB209” (MAFF, 2000).

Farm typology descriptions

Farm-scale estimates of the cost and effectiveness of the mitigation methods refer to the twelve farm typologies presented in Tables A1 to A3, which are described in further detail below. Effectiveness was assessed for the area each method was applied to (at the farm scale) on each farm typology for permeable (free drained) and impermeable (poorly drained) soils located in the moderate to high rainfall (700-900 mm) climate. For farms on medium/heavy soils, the fields were assumed to have functioning drains on 70% of the land area.

Dairy

The dairy farm typology had 110 dairy cows, 28 heifers and an additional 59 followers (i.e. cattle more that one year old). Ten percent of the grassland area was re-seeded each year. The average field size was 8 ha. The farm also had 5 ha of cereals, 6 ha of forage maize and 2 ha of stubble turnips (total area 114ha).

Total excreta production was estimated at 3,246 tonnes. The dairy cows were 'housed' for 248 days each year (including time spent on collecting yards and in the milking parlour during the grazing season), and used collecting yards, feeding yards and self-feed silage yards (in winter only). A total of 62% of the excreta was deposited during 'housing' (with the remainder at grazing) and was managed as slurry and stored for 3 months. The slurry was assumed to be stored in a tin tank 4 m tall and 15 m diameter. All managed slurry was assumed to be spread across the grassland area. Sheep and cattle (less than two years old) were kept on straw and FYM was stored in an open field site. A total of 70% of the FYM was spread after storage and 30% spread direct (i.e. 'fresh').

The managed slurry was diluted during storage (due to rainfall and wash water inputs), so that the dry matter content was reduced from 10 to 6%. Total N production was 18,400 kg N annually, giving a livestock manure N farm loading of 161 kg N/ha. The total amount of slurry produced was around 2,600 tonnes. Dirty water was collected in a separate store and spread on 5% of the permanent grassland area. Approximately 50% of the grassland area received slurry at 50 m^3/ha and 70% of the forage maize area received FYM at 35 t/ha, with approximately 70% of the slurry spread between November and April and 70% of the FYM spread in the spring (February to April). The grassland area also received an average N fertiliser application rate of 127 kg N/ha and average phosphate application rate of 18 kg P_2O_5/ha, with 7% of N fertiliser applied as urea.

LFA (Less Favoured Area) Grazing

An all grass farm of 146 ha; with 67 ha of enclosed (permanent and temporary) grassland and 79 ha of rough grazing. The cattle herd had 37 adult beef animals, plus 35 progeny (20 calves and 15 yearlings). There were also 358 sheep and 339 lambs. Fertiliser N rates were 47 kg N/ha on permanent grassland and 90 kg N/ha on temporary grassland. No fertiliser was applied to the rough grazing land. In total, 43 ha of land was used for silage making (a single cut was taken on 19 ha and two cuts on the remaining 24 ha) and 25 ha was grazed only. Overall (average) fertiliser application rates were 50 kg/ha N and 15 kg/ha P_2O_5.

Total N production was 8,890 kg N annually, giving a livestock manure N farm loading of 61 kg N/ha. Calving was assumed to take place in spring, with young stock taken through two winters before being sold at 18-24 months of age. Adult cattle and yearlings had access to concrete yards for feeding in winter. No significant quantities of slurry were generated. Lambs were weaned for five months and sold as store lambs in the autumn. FYM production was estimated at around 440 tonnes per annum; 70% of the FYM was stored for 3 months in field heaps prior to land spreading and 30% was spread direct (i.e.' fresh'). Approximately 25% of the FYM was applied in autumn (August-October), 30% in winter (November-January), 35% in spring (February-April) and 10% in summer (May-July) at an average application rate of 20 t/ha.

Lowland Grazing

The lowland grazing farm had an area of 101 ha comprising 91 ha of enclosed (permanent/temporary) grassland, 4 ha of rough grazing and 6 ha of arable land. The cattle herd had 44 adult beef cattle and 77 progeny (39 calves and 38 yearlings). The sheep flock had 184 sheep and 170 lambs. Fertiliser N rates were 47 kg N/ha on permanent grassland

and 90 kg N/ha on temporary grassland. No fertiliser was applied to the rough grazing land. In total, 66 ha of land was used for silage making (a single cut was taken on 28 ha and two cuts on the remaining 38 ha) and 36 ha was grazed only. Overall (average) grassland fertiliser application rates were 55 kg/ha N and 16 kg/ha P_2O_5. The average fertiliser N rates applied to winter barley, spring barley and maize were 118, 95 and 31 kg/ha, respectively.

Total N production was 9,012 kg N annually, giving a livestock manure N farm loading of 89 kg N/ha. Calving was assumed to take place in spring, with young stock taken through two winters before being sold at 18-24 months of age. Adult cattle and yearlings had access to concrete yards for feeding in winter. No significant quantities of slurry were generated. Lambs were weaned for three to four months and finished primarily on grass to 10-12 months of age. FYM production was estimated at around 650 tonnes per annum. 70% of the FYM was stored for 3 months in field heaps prior to spreading and 30% was spread direct (i.e. 'fresh'). Approximately 30% of the FYM was applied in autumn (August-October), 25% in winter (November-January), 30% in spring (February-April) and 10% in summer (May-July) at an average application rate of 20 t/ha.

Mixed

The 'mixed' farm had an area of 155 ha, with 96 ha of enclosed grassland (permanent/temporary), 5 ha of rough grazing and 54 ha of tillage land. All cereal land was ploughed and 'heavy' discs were used for oilseed rape establishment. There were 31 adult dairy cows, 32 followers, 52 beef cattle, 40 calves, 190 sheep and 203 lambs on the farm. The (small) pig enterprise had 2 boars, 5 dry sows (120 kg liveweight-lwt), 15 farrowing sows (200 kg lwt), 9 gilts not yet in pig, 106 weaners (10 kg lwt), 102 first stage grower (35 kg lwt) places, 92 second stage grower (65 kg lwt) places, 65 finisher (95 kg lwt) places and 4 pigs over 110 kg lwt. The (small) poultry unit had 2,605 bird places, including layers, pullets, broilers, turkeys, breeding birds and ducks. Ninety percent of pig diets, 90% of layer and 40% of broiler rations contained phytase. All cattle were kept on FYM; pig manure was managed as both FYM and slurry. The laying hens were on a solid manure system, ducks on a straw-based system and the remaining birds on a litter based system.

Total manure N production was 19,975 kg N annually, giving a livestock manure N farm loading of 129 kg N/ha. Total manure production was around 1,900 tonnes (Cottrill and Smith, 2010). Seventy percent of cattle, sheep and pig FYM was stored before spreading, and 50% of poultry manure was stored ahead of spreading, with the remainder spread direct (i.e. 'fresh'). Pig slurry was stored in a pit below the buildings and solid manure was stored in field heaps (for 3 months or more). Washwater and runoff from the dairy and beef collecting and feeding yards was collected in a dirty water store. The manures were spread across the grassland and tillage land areas.

The enclosed grassland received an average fertiliser N application rate of 77 kg/ha N and average phosphate fertiliser application rate of 29 kg/ha P_2O_5. Arable (tillage) land received an average fertiliser N application rate of 128 kg/ha N and average phosphate fertiliser application rate of 30 kg P_2O_5/ha. On tillage land, 30% of fertiliser N was applied as urea and on grassland 7% of fertiliser N was applied as urea.

Combinable cropping

The combinable cropping farm had 172 ha of (mixed) combinable crops. The average field size was 8 ha. The crops received an average fertiliser N application rate of 188 kg N/ha and an average phosphate fertiliser application rate of 43 kg P_2O_5/ha. Thirty percent of fertiliser N was applied as urea. Around 10% of the farm area grew spring combinable crops. All the cereal land was ploughed, with 'heavy' discs used for oilseed rape establishment.

Combinable cropping–with manure

The combinable cropping-farm with manure had an area of 172 ha, with the same cropping and cultivation practices as the combinable cropping farm without manure. This farm typology received all of the solid farmyard manure (FYM) and slurry produced on the 'indoor pigs' farm, which amounted to 25,100 kg total N and had a livestock manure N farm loading of 146 kg N/ha. Thirty percent of the pig FYM was spread direct from housing (i.e. 'fresh') and 70% was stacked in field heaps (for >3 months) prior to land spreading. The FYM was spread at a rate of 35 t/ha and pig slurry at 50 m^3/ha. Approximately 50% of the pig slurry was applied in autumn (August-October), 20% in winter (November-January), 30% in spring (February-April) and none in summer (May-July). For pig FYM, 80% was applied in autumn (August-October), 10% in winter (November-January), 10% in spring (February-April) and none in summer (May-July). The crops received an average fertiliser N application rate of 180 kg N/ha and average phosphate fertiliser application rate of 38 kg P_2O_5/ha; fields where manure was applied had their fertiliser application rates adjusted based on date from Goodlass and Welch (2005). Thirty percent of fertiliser N was applied as urea.

Roots and combinable cropping

The roots/combinable cropping farm had an area of 180 ha. The average field size was 8 ha. The crops received an average fertiliser N application rate of 151 kg N/ha and an average phosphate fertiliser application rate of 48 kg P_2O_5/ha. Thirty percent of fertiliser N was applied as urea. Around 50% of the farm area grew spring combinable crops, and had 15 ha of permanent grassland. All of the tillage land was ploughed.

Roots and combinable cropping–with manure

The roots/combinable cropping farm with manure had an area of 80 ha; with the same cropping and cultivation practices as for the roots/combinable cropping farm without manure. This farm typology received poultry manure from the 'specialist poultry' farm. This amounted to 16,280 kg total N (i.e. half the amount produced by each 'specialist poultry' farm) and had a livestock manure N farm loading of 90 kg N/ha. Half of the poultry manure was spread direct from housing (i.e. 'fresh') and half was stacked in field heaps (for >3 months) prior to spreading. The poultry manure was spread at a rate of 10 t/ha, with approximately 65% applied in autumn (August-October), 15% in winter (November-January), 20% in spring (February-April) and none in summer (May-July). The crops received an average fertiliser N application rate of 149 kg N/ha and average phosphate fertiliser application rate of 47 kg P_2O_5/ha; fields where manure was applied has their fertiliser application rates adjusted based on data from Goodlass and Welch (2005). Thirty percent of fertiliser N was applied as urea.

Indoor pigs

The 'indoor pigs' farm had no land for crop production. There were 6 boars, 204 dry sows (120kg lwt), 159 farrowing sows (200kg lwt), 1,272 weaners (10 kg lwt), 983 first stage grower (35 kg lwt) places, 621 second stage grower (65 kg lwt) places, 247 finisher (95 kg lwt) places and 32 pigs over 110 kg lwt. Total (undiluted) excreta production was 4,390 tonnes annually, which was handled as both FYM and slurry. Slurry was stored in a pit below slatted floors in the livestock building, with 3 months storage capacity. During storage the slurry was diluted with rain/wash water etc. resulting in a slurry volume of 1,500 m^3 and a dry matter content of 4%. Total N production was 25,100 kg N annually. Ninety percent of diets were assumed to contain phytase. All of the pig slurry and FYM was exported to the 'Combinable cropping–with manure' farm typology.

Outdoor Pigs

The 'Outdoor pigs' farm had a breeding unit, with piglets moved to a growing unit at 7 kg. These were 140 dry sows, 294 farrowing sows and 6 boars.

The sows were assumed to deposit excreta across the whole of the free range dunging area; the approximate stocking rate was 25 sows/ha, over an area of 18 ha. Farrowing huts were moved after every litter, but there was no collection or storage of manure. Annual excreta production was 1,500 m^3, with a total N content of 9,200 kg N (Cottrill and Smith, 2010).

Specialist poultry

The ‘specialist poultry’ farm had no land for crop production. There were 81,351 bird places, including laying hens, pullets, broilers, turkeys, breeding birds and ducks. In total, 90% of laying hen and 40% of broiler rations contained phytase. The laying hens produced solid manure, the ducks straw-based FYM and the remaining birds poultry litter. Total manure production was 2,160 tonnes (Cottrill and Smith, 2010), with 34% of broiler and turkey litter sent for incineration (Webb and Misselbrook, 2004), leaving 1720 tonnes of poultry manure for land spreading. The total annual N content of all the manures (post housing and storage) was 32,570 kg N. All of the manure from each specialist poultry farm was spread on the equivalent of two ‘roots and combinable cropping–with manure’ farms.

Horticulture

The ‘horticulture’ farm had an area of 18 ha, with no livestock and no imported manures. There were 3 ha of permanent grassland and 15 hectares of horticultural crops; including cauliflowers (4 ha), carrots (4 ha), apples (5 ha) and strawberries (2 ha). The crops received an average fertiliser N application rate of 103 kg N/ha and average phosphate fertiliser application rate of 47 kg P_2O_5/ha. Eleven percent of N fertiliser was applied as urea.

APPENDIX II. ASSUMPTIONS USED IN DERIVING COST-ESTIMATES

The 'broad' cost estimates below should be used for guidance only and will vary with the detail of method implementation, farm size, the make-up of the farm enterprise and the response of the farming system to method implementation.

Negative figures are negative costs i.e. they represent a saving or increased income.

Many of the costs involve amortised capital which is indicated against each method. The annual charge for any capital investment required was derived by amortising the required investment over the anticipated write-off period (at an interest rate of 7%).

Method 1a – Convert arable land to unfertilised and ungrazed grassland

The method was applied to 10% of all arable land on the relevant farm type, no manure or fertiliser was applied to the arable reversion land. The land was left to regenerate following harvest with no cultivation and no grass seeding; the regrowth was 'topped' one year in five. No sale of machinery was involved. Costs were based on loss of income, using figures from Nix (2008).

Cost: £100/ha

Method 1B – Arable reversion to low fertiliser input extensive grazing

All of the arable land was converted to extensive grassland at low stocking rates. Costs were based on the sale of machinery, net the cost of the livestock used on the extensive grassland. Costs cover loss of income from arable cropping and grassland establishment.
It was assumed that the farm had general purpose buildings which could be used to store machinery or to house livestock. Livestock depreciation was included at 25%, along with the amortised costs (over 10 years) of fencing, hedging and water supply provision. No allowance was made for any issues of redundancy and accommodation if any farm workers were involved. A loss of rental value of the land was included at £50/ha.

Costs: £100/ha for arable land; £2,000/ha for horticultural land.

Method 2 – Convert arable/grassland to permanent woodlands

This is a long-term change where broadleaf woodland is grown in place of agricultural crops, with a rotation length of around 75 years. During this time, some income may be generated, but most of the value will be realised when the woodland is clear felled. The negative cost will vary with farm type dependent on net margin; the figure was not subject to amortisation or net present value calculations.

Cost: -£150/ha (based on whole life cycle cost/income over 75 years).

Method 3 – Convert land to biomass cropping

As with woodlands, this is a change in land use and profitability will depend on the market value of the output at the time of harvest (which can vary significantly within and between markets). The market was assumed to be power station co-firing (for local use the income would be more). The figures were not amortised or expressed as net present value. Costs were based on income from *Miscanthus* on a 15 year rotation and no planting grant, minus the gross margin loss from previous agricultural cropping.

Cost: -£10/ha (but may be up to - £150/ha).

Method 4 – Establish cover crops in the autumn
Costs based on cultivating and drilling a cover crop (not simply leaving the land to regenerate following the previous crop).

Cost: £60/ha.

Method 5 – Early harvesting and establishment of crops in the autumn
Costs based on a change to earlier harvested maize varieties which produce the same yield. For potatoes, a change from maincrop to second earlies produced a lower gross margin for that crop, which was only partly compensated by an improved gross margin in the following wheat crop.

Cost: £800/ha for potatoes.

Method 6 – Cultivate land for crops in spring rather than autumn
Costs based on a 25% reduction in spring combinable crop yields. Costs for grassland were based on ploughing out in spring and a 25% loss in grass yields.

Cost: £100/ha.

Method 7 – Adopt reduced cultivation systems
A contractor was assumed to be used and the plough retained for occasional use in difficult seasons. The net effect from selling most cultivation equipment and using a contractor was a saving of -£40/ha.

Cost: -£40/ha

Method 8 – Cultivate compacted tillage soils
Costs based on a light cultivation @ £25/ha (carried out annually on 20% of the arable land).

Cost (overall): £5/ha.

Method 9 – Cultivate and drill across the slope
Costs based on additional time taken for contour cultivations @ £10/ha.

Method 10 – Leave autumn seedbeds rough
Costs based on ‘poorer’ crop establishment (and a small yield loss) plus additional costs for pest/weed control.

Cost: £40/ha.

Method 11 – Manage over-winter tramlines
Costs based on a light cultivation to remove the compaction and channelling created by tramlines.

Cost: £10/ha.

Method 12 – Maintain and enhance soil organic matter levels
On the farms receiving organic manures, the costs include savings on manufactured fertiliser inputs and the costs of transport over 3 km and 10 km distances

Cost: -£170/ha for 3 km
Cost: £20/ha for 10 km.

Method 13 – Establish in-field grass buffer strips
Costs based on grass strip establishment in cropped fields (with no backfencing), the loss of output and topping management.

Method 14 – Establish riparian buffer strips
On grassland fields, the costs include fencing, but not grass establishment. On arable fields, the costs include cover establishment, but not fencing. Costs were based on loss of output, grass establishment (and fencing) and topping management activities.

Method 15 – Loosen compacted soil layers in grassland fields
Costs based on topsoil loosening @ £40/ha (carried out every four years on each of the grassland fields).

Cost (overall): £10/ha.

Method 16 – Allow field drainage systems to deteriorate
Yield losses were estimated to be in the range 5-10%, due to poor drainage on both arable land and grassland.

Costs: £50/ha arable; £10/ha grassland.

Method 17 – Maintain/improve field drainage systems
Costs based on the need to mole drain every five years (on to 20% of the farm annually).

Cost (overall): £10/ha.

Method 18 – Ditch management
Ditch clearance was costed at contractor rates, using a machine with an excavation bucket on 20% of the farm annually.

Cost (overall): £18/ha.

Method 19 – Make use of improved genetic resources in livestock
Variable (input) costs were estimated to be reduced by around 10% for the same amount of livestock output.

Cost: -£80 per dairy cow.

Method 20 – Use plants with improved nitrogen use efficiency
Costs based on reduced fertiliser N inputs for the same amount of crop production.

Cost: Arable -£20/ha.

Method 21 – Fertiliser spreader calibration
Costs based on average contractor rates.

Cost: £150 per farm.

Method 22 – Use a fertiliser recommendation system
Cost savings based on more efficient use of manufactured fertiliser inputs.

Cost: -£5/ha grassland; -£10/ha arable land.

Method 23 – Integrate fertiliser and manure nutrient supply
Cost savings based on greater allowance being made for manure nutrients and associated reductions in manufactured fertiliser inputs where manure applied.

Cost: -£15/ha grassland; -£30/ha arable land

Method 24 – Reduce manufactured fertiliser application rates
Estimated to produce a reduction in gross margin (costs vary across the farm types).

Method 25 – Do not apply manufactured fertiliser to high-risk areas
Costs based on (small) yield reductions on high-risk areas.

Costs: £5/ha arable land: £1/ha grassland.

Method 26 – Avoid spreading manufactured fertiliser to fields at high-risk times
Costs based on a (small) yield reduction as a result of ‘delayed’ fertiliser application.

Cost: £5/ha arable land; £1/ha grassland.

Method 27 – Use manufactured fertiliser placement technologies
Costs based on additional operational inputs.

Cost: £2/ha.

Method 28 – Use nitrification inhibitors
Costs based on inhibitor purchase/application.

Cost: £20/ha.

Method 29 - Replace urea fertiliser with another nitrogen form
Although urea is cheaper than ammonium nitrate per unit of N, higher ammonia losses from urea result in a (small) yield penalty compared with ammonium nitrate.

Cost: -£5/ha.

Method 30 - Incorporate a urease inhibitor into urea fertilisers
Costs based on urease inhibitor being added to the fertiliser at source and that the increased fertiliser cost was balanced by increased crop yields (as a result of lower NH_3 losses). Cost: neutral.

Method 31 - Use clover in place of fertiliser nitrogen
Costs based on productivity being maintained, with the cost of establishing (and managing) clover in grass swards offset by savings in manufactured fertiliser N use. Cost: neutral.

Method 32 - Do not apply P fertiliser to high P index soils
Costs based on P fertiliser savings on high P index soils (estimated to occupy 10% of farm area).

Cost (overall): -£3 to 6/ha.

Method 33 - Reduce dietary N and P intakes
Costs based on cereal feed being used to replace high N forage.

Cost: £0.01/head for poultry and £45/dairy cow.

Method 34 – Adopt phase feeding of livestock
Costs based on collars (with transponders) being fitted to dairy cows and sows, along with the use of feed dispensers. Costs have been amortised over 5 years.

Cost: £0.75/m^3 slurry (amortised).

Method 35 – Reduce the length of the grazing day/grazing season
Costs based on additional building floor scraping and slurry handling, together with additional silage production to feed the housed livestock. We have assumed that no additional slurry storage was needed.

Cost: £0.70-1.80/m^3 slurry.

Method 36 – Extend the grazing season for cattle
Cost savings based on the reduced need for building floor scraping and slurry handling, together with reduced silage production costs.

Cost: -£0.50/m^3.

Method 37 – Reduce field stocking rates when soils are wet
Costs based on additional silage production, floor scraping and slurry handling. We have assumed that no additional slurry storage was needed.

Cost: £0.70-1.80/m^3 slurry.

Method 38 – Move feeders at frequent intervals
Costs based on moving feeding troughs on a fortnightly basis for dairy/beef cattle during the grazing season, and for pigs throughout the year. Costs include capital purchase of feeders and were amortised over 10 years

Cost: £10-30/ha (amortised).

Method 39 – Construct troughs with a firm but permeable base
Costs based on constructing a concrete base for existing troughs and are amortised over 10 years (large round troughs for dairy cattle, and conventional troughs for beef, sheep and pigs).

Cost: £2-5/ha (amortised)

Method 40 – Improved feed characterisation
Costs of feed formulation have been assessed to be balanced by improved feed utilisation (i.e. there is no net cost). Cost: neutral

Method 41 – Reduce overall stocking rates on livestock farms
Costs are based on the loss of gross margin.

Method 42 – Increase scraping frequency in dairy cow cubicle housing
Costs are based on the extra working time for a tractor and worker (and assume no need for further capital investment).

Cost: £2/m^3 slurry.

Method 43 – Additional targeted bedding for straw-bedded cattle housing
Costs based on the additional time to remove and spread FYM, and additional straw costs.

Cost: £3/tonne FYM.

Method 44 – Washing down of dairy cow collecting yards
Costs based on an additional 25 litres of washwater per cow.

Cost: £70/dairy cow.

Method 45 – Outwintering of cattle on woodchip stand-off pads
Costs based on the need to excavate to 0.75m depth, line the pad and install drainage, and were amortised over 5 years.

Cost: £50/head of cattle (amortised).

Method 46 – Frequent removal of slurry from beneath-slatted storage in pig housing
Costs based on more frequently pumping out of underfloor storage and the provision of additional slurry storage and were amortised over 20 years.

Cost: £2/m^3 slurry (amortised).

Method 47 – Part-slatted floor design for pig housing
Costs based on replacing a solid concrete floor with part slats and were amortised over 20 years.

Cost: £2.50/m^3 slurry (amortised).

Method 48 – Install air-scrubbers or biotrickling filters to mechanically ventilated pig housing
Costs based on the installation of air-scrubbers or filters and were amortised over 5 years.

Cost: £5.50/m^3 slurry (amortised).

Method 49 – Convert caged laying hen housing from deep storage to belt manure removal
Costs base on the installation of new cages and belts and were amortised over 10 years.

Cost: £35/t manure (amortised).

Method 50 – More frequent manure removal from laying hen housing with belt clean systems
Costs based on the increased frequency of running belt systems.

Cost: £0.10/t manure.

Method 51 – In-house poultry manure drying
Costs based on the installation and running of drying equipment and were amortised over 5 years.

Cost: £0.50/t manure (amortised).

Method 52 – Increase the capacity of farm manure (slurry) stores to improve timing of slurry applications
Costs based on the construction of additional slurry storage and were amortised over 20 years.

Cost: £4/m^3 slurry (amortised).

Method 53 – Adopt batch storage of slurry
Costs based on the construction of additional slurry storage and were amortised over 20 years.

Cost: £4/m^3 slurry (amortised).

Method 54 – Install covers on slurry stores
Costs based on the installation of a store cover and were amortised over 10 years.

Cost: £1.10/m^3 slurry (amortised).

Method 55 – Allow cattle slurry stores to develop a natural crust
Costs based on the installation and running of a ‘larger’ stirrer to facilitate emptying and were amortised over 5 years.

Cost: £0.15/m^3 slurry (amortised).

Method 56 – Use anaerobic digestion for farm manures
Costs based on the capital investment needed to set-up an anaerobic digestion plant (with no additional slurry storage needed) and were amortised over 20 years.

Method 57 – Minimise the volume of dirty water produced
Costs based on additional roofing (over dirty concrete areas) and diversion of ‘clean’ water and were amortised over 20 years.

Cost: £40/m^2 roof (amortised).

Method 58 – Adopt batch storage of solid manure
Costs based on the construction of concrete pad/leachate collection facilities and associated areas for vehicle movements, and were amortised over 20 years.

Cost: £1/t solid manure (amortised).

Method 59 – Compost solid manure
Costs based on the turning of FYM windrows (twice), using a tractor and front-end loader.

Cost: £2.60/t solid manure.

Method 60 – Site solid manure heaps away from watercourses/field drains
Costs based on the additional time needed to plan the siting of manure heaps.

Cost: £1/ha.

Method 61 – Store solid manure heaps on concrete and collect leachate
Costs based on the construction of concrete pad/leachate collection facilities and associated areas for vehicle movements, and were amortised over 20 years.

Cost: £1/t solid manure (amortised).

Method 62 – Cover solid manure stores with sheeting
Costs based on the provision of sheeting.

Cost: £0.50/t solid manure.

Method 63 – Use liquid/solid manure separation techniques
Costs cover purchase of a slurry separator and provision of a concrete pad to store the solids (the separated liquid is pumped to a slurry store) and were amortised over 10 years.

Cost: £2-4/m^3 of slurry (amortised).

Method 64 – Manure additives (e.g. Alum)
Costs based on Alum purchase and addition to poultry litter.

Cost: £3/t litter.

Method 65 – Change from a slurry to solid manure handling system
Costs based on changes to livestock buildings for housing, straw costs and additional labour requirements. On the indoor pig farm, the method would involve complete renewal of stock due to the break in production while the housing system was being re-designed. Costs were amortised over 20 years.

Costs: around £13,000 for dairy unit; around £30,000 for pig unit.

Method 66 – Change from solid manure to slurry handling system
Costs based on the installation of cubicles in cattle housing and construction of a slurry storage tank and were amortised over 20 years.

Costs: around £18,000 for dairy unit; around £30,000 for pig unit.

Method 67 – Manure spreader calibration
Costs based on the time needed to assess evenness of manure spreading and field application rates.

Cost: £200 per farm.

Method 68 – Do not apply manure to high-risk areas
Costs based on additional management time to plan manure spreading activities.

Cost: £1/ha.

Method 69 – Do not spread slurry or poultry manure at high-risk times
Costs based on additional management time to plan manure spreading activities.

Cost: £1/ha.

Method 70 – Use slurry band spreading application techniques
Costs based on the use of a contractor (above standard broadcast spreading costs).

Cost: £1/m^3 slurry.

Method 71 – Use slurry injection application techniques
Costs based on the use of a contractor (above standard broadcast spreading costs).

Cost: £1.50/m^3 slurry.

Method 72 – Do not spread FYM to fields at high-risk times
Costs based on additional management time to plan FYM spreading activities.

Cost: £1/ha.

Method 73 – Incorporate manure into the soil
Costs based on an additional plough-based cultivation.

Cost: £45/ha.

Method 74 – Transport manure to neighbouring farms
Costs based on the need to transport manure over 5 km.

Cost: £5/m^3 slurry; £4/t solid manure.

Method 75 – Incinerate poultry litter for energy recovery
Costs based on the need to replace poultry litter nutrients with manufactured fertiliser nutrients (on the ‘roots and combinable crops’ farm); transport of the litter to the energy plant is generally cost neutral for the poultry producer.

Cost: £30/ha.

Method 76 – Fence off rivers and streams from livestock
Costs based on the provision of standard seven wire fencing and water troughs and were amortised over 10 years.

Cost: £5-15/ha (amortised)

Method 77 – Construct bridges for livestock crossing rivers/streams
Costs based on the construction of two bridges per farm and were amortised over 10 years.

Cost: £5-30/ha (amortised)

Method 78 – Re-site gateways away from high-risk areas
Costs based on the removal of gateways and replacement with back fenced hedging on *c.*30% of fields and were amortised over 10 years.

Cost: £2-4/ha (amortised)

Method 79 – Farm track management
Costs based on digging out a soakaway and installing French drains across farm tracks, plus maintenance and clearing out every four years, and were amortised over 10 years.

Cost: £1-3/ha (amortised)

Method 80 – Establish new hedges
Costs based on new hedge establishment, installing new gateways and back fencing, and were amortised over 10 years.

Cost: £25-70/ha (amortised)

Method 81 – Establish and maintain artificial wetlands
Costs based on a reedbed for dairy steadings, and a wetland (bunded and fenced) for arable land (covering 0.25% of the arable area) and associated crop production losses. Investment costs were amortised over 20 years.

Costs: £15/ha of arable land; £200 for dairy farm (amortised)

Method 82 – Irrigate crop to achieve maximum yield
Costs based on licensing, water storage and irrigation equipment, and the annual operational costs of water application. Costs were amortised over 20 years.

Cost: around £1,000/ha (amortised)

Method 83 - Establish tree shelter belts around livestock housing
Costs based on the establishment of a 30m deep shelter belt of trees around the perimeter of the livestock building/slurry store (approximately 1 ha was required on the dairy unit and 2 ha on the pig unit). Costs were amortised over 20 years.

Costs: around £400 for dairy farm; £800 for pig farm (amortised)

APPENDIX III. GLOSSARY

Definitions followed by [R] are taken from Pain, B. & Menzi, H. (2003). *Glossary of Terms on Livestock Manure Management.*

AGGREGATE STABILITY	The cohesive strength of the forces binding together individual soil particles within a crumb or block of soil.
AMINO ACIDS	The chemical units that link together to form proteins and are of fundamental importance to life. [R]
AMMONIA	NH_3. A gas derived from urea excreted by livestock (and from uric-acid excreted by poultry) and implicated in acidification and N enrichment of sensitive ecosystems. [R]. NH_3 volatilisation can occur from urine patches in the field, from animal houses and yards, during and following manure application, and from some N fertilisers etc.
AMMONIUM	NH_4^+. Positively charged ionic form of mineral N, present in soils, fertilisers and manures. It is not readily leached from soils because it is attracted to soil particles, but can be lost in surface RUNOFF and MACRO-PORE FLOW where there is only limited contact between the flowing water and soil surfaces. Ammonium in soils is converted to nitrate by the process of NITRIFICATION.
AMORTISED CAPITAL COST	An annual cost derived from spreading the capital cost of an item over a given number of years, at a given interest rate. The number of years will vary with the durability of the item; for example, a concrete pad may be costed over 20 years and a fence over 5 years.
ANAEROBIC	Condition of soils, manures etc. where there is an absence of free oxygen. This restricts biological activity to those organisms that can live and grow without free oxygen.
ARABLE REVERSION GRASSLAND	Arable land that has been changed to (low input) grassland, either through natural regeneration or by seeding with a suitable grass/wild flower mixture. Usually managed by cutting and grazing to maximise wildlife benefits.
BATCH STORAGE	Treatment method for manures in which, once a quantity of manure has been collected, it is stored without further additions of ‘fresh’ manure.
BIOLOGICALLY FIXED N	Refers to N obtained by the process of symbiotic N fixation in legumes, whereby N-fixing bacteria (*Rhizobia*) in nodules on the roots of leguminous plants fix di-nitrogen gas from the atmosphere and supply the host plant with N in exchange for a supply of carbohydrate. This fixed N is able to substitute for N uptake from the soil, mineral fertiliser or manure additions.
BOD	Biochemical Oxygen Demand. A measure of the (water) pollution potential of organic materials etc. A laboratory test is used to measure the amount of dissolved oxygen consumed by chemical and biological action when a sample is incubated at 20^oC for a given number of days. [R]; usually 5 days. Surface waters with a high BOD, contain high concentrations of potentially oxidisable organic matter, and decomposition utilises dissolved oxygen in the water, depleting free oxygen levels and the ability of the water body to support many forms of animal life.
BOLTING	Early flowering of a plant (e.g. cabbages, lettuce) before it fully develops as a crop.
BROADCAST	Sowing by scattering seed (uniformly) over the surface of an area of land (as opposed to placement of seed in drills or rows). Similarly, refers to broadcasting of fertiliser or manure over the whole surface of an area of land.

BROILER	A chicken reared for meat production. [R]
BUFFER FEED	Typically hay or silage fed to livestock in the field, at times during the grazing season, when fresh grass is in short supply.
BUFFER STRIP	A strip of grassland or other vegetation located between cultivated areas or fields to minimise surface runoff and soil erosion. Also, used between fields and watercourses. [R]
BY-PASS FLOW	See MACRO-PORE FLOW
CAPPING	Creation of a thin crust on the surface of soil, which restricts the infiltration of rainwater and increases surface RUNOFF.
CARBON SEQUESTRATION	A process that removes carbon dioxide from the atmosphere to mitigate global warming, for example, through increasing the amount of carbon (organic matter) in soils by reverting arable land to grassland, establishing woodlands etc.
CLOSED PERIOD	Nitrate Vulnerable Zone rules define closed (spreading) periods for arable land and grassland, during which applications of N fertiliser and high readily available N manure applications (e.g. livestock slurries, poultry manure applications) are not permitted.
COARSE-TEXTURED SOILS	Soils with a high proportion of sand and coarse silt particles. These soils are free draining and are easily worked; and generally contain less than 18% clay.
COMBINABLE CROPS	Crops that produce a hard seed that is suitable for harvesting with a combine harvester (e.g. cereals, beans, oilseed rape etc.).
COMPACTION	An increase in soil bulk density (mass per unit volume) and decrease in porosity resulting from applied loads, vibration or pressure. Soil compaction decreases the water holding capacity and air content of the soil, can impede plant (root) growth and increases the risk of surface runoff and erosion. [R]
COMPOSTING	The breakdown (stabilisation) of SOLID MANURES (materials) in the presence of free oxygen i.e. under aerobic conditions. ‘Active’ composting can be achieved by mechanical turning or mixing a heap or pile to incorporate air. [R]
COMPOUND (FEED)	Livestock feed composed of several different feeding stuffs, minerals and trace elements in proportions to provide a balanced ration or diet. [R]
CONSTRUCTED WETLAND	A constructed, semi-natural area of land typically comprising beds of specialised plants such as reeds (*Phragmites* spp.) and gravel filled channels [R].
COVER CROP	A (rapidly) growing crop sown in autumn for the purpose of taking up soil mineral nitrogen which would otherwise be at risk of loss by over-winter nitrate leaching and/or protecting the soil from the erosive impact of rainfall.
CROP OFFTAKE	Amount of nutrients removed from a field in the harvested crop.
CROP RESIDUES	The unharvested part of a crop that is left in the field e.g. straw, leaf material and stubble (and crop roots).
CUBICLE (house)	A building divided into rows of individual stalls or cubicles in which animals lie when at rest, but are not restrained. A small amount of bedding (e.g. sawdust, wood shavings, chopped straw, sand, rubber or plastic mats) is placed in each cubicle. Faeces and urine are excreted into passageways between the cubicles, with the passageways periodically cleaned and the manure removed as SLURRY. [R]
DAIRY CAKE	A general term for processed feedstuffs for dairy cattle, with a high food value relative to volume and a low fibre content. May be rich in protein, carbohydrate or fat. [R]

DENITRIFICATION	The transformation, most commonly by bacteria, of nitrate to nitrous oxide and di-nitrogen gas. An anaerobic process that occurs in soils and manure stores and some manure treatment methods after nitrification. [R]
DI-NITROGEN	N_2. The (harmless) form of nitrogen gas that constitutes 78% of the earth’s atmosphere.
DIRTY WATER	Water derived from washing of equipment and floors in milking parlours, rainfall runoff from concrete or hard-standing areas used by livestock and contaminated with faeces, urine, waste animal feed etc. Contains organic matter and so poses a risk of water pollution, but has a negligible (low) fertiliser value. [R]
EROSION	Wearing away and loss of soil, principally topsoil, by wind and running water. [R]
FACTS	Fertiliser Advisers Certification and Training Scheme
FARMYARD MANURE (FYM)	Faeces and urine mixed with large amounts of bedding (usually straw) on the floors of cattle or pig housing. May also include horse or stable manure. [R]
FERTILISER RECOMMENDATION SYSTEM	A system to provide advice to farmers about how much fertiliser to apply to obtain the best financial return, while minimising nutrient losses to the wider environment. Recommendations take account of crop requirements, soil type, existing levels of nutrients in the soil and the nutrients supplied by organic manures etc. This information can be supplied in book form (e.g. “The Fertiliser Manual (RB209)” or as a computer-based package (e.g. PLANET; www.planet4farmers.co.uk).
FINE-TEXTURED SOILS	Soils with a high proportion of clay and fine silt particles. They usually have poor natural drainage and are ‘difficult’ to work; and generally contain more than 18% clay.
FINISHING (pigs)	Growth stage of pigs, between 60 kg and slaughter. [R]
FIO	Faecal Indicator Organism. Microorganisms excreted by and present in livestock excreta and manures. Their presence in water indicates contamination by excreta manure; *E.coli* is the most commonly used FIO.
FIXED N	See BIOLOGICALLY FIXED N
FLATLIFTING	Method of soil loosening using specialised mechanical equipment to break-up compacted soil pans (above a depth of *c*.35cm), but with minimal surface disturbance.
FOLLOWERS	Young stock on a dairy farm not yet in milk, but growing to become dairy cows. [R]
FORAGE	Crops consumed in the green state by livestock e.g. grass, kale, maize, lucerne, or made into silage. [R]
‘FRESH’ SOLID MANURE	Solid manure immediately after removal from livestock housing. [R]
GROUNDWATER	Water that flows or seeps downwards and saturates soil or rock, supplying springs and wells. The upper surface of the saturated zone is called the WATER TABLE. [R]
GULLY EROSION	A more severe development of RILL EROSION, in which the further concentration of surface water flow into erosion channels increases the flow rate and erosive force of the water sufficiently to remove large quantities of topsoil and subsoil to create deep, wide gullies that cannot be ‘corrected’ by normal agricultural field operations.
HARDSTANDING	A general term for any outdoor, normally unroofed, area with a hard surface, usually of concrete (including dairy cow collecting yards, feeding yards, farmyard manure storage areas). [R]

HEAVY SOILS	See FINE-TEXTURED SOILS
HILLSIDE COMBINE	Combine harvester designed to operate efficiently when travelling across a slope.
HYDROLOGICAL CONNECTIVITY	Water-mediated transfer of matter, energy and/or organisms, within or between, elements of the hydrologic cycle. Water flow paths that run into one another (e.g. field drains or a culvert running directly into a stream) will have a high degree of connectivity.
INCIDENTAL LOSSES	Pollutant losses that occur when rainfall creates runoff shortly after the land application of fertiliser, manure and excreta, even where good practice has been followed.
K	Potassium
LAYING (of hedges)	Practice of hedge management necessary for the establishment of hedges and to prevent their deterioration. Partly-cut stems are bent and laid sideways to reinvigorate growth and to help plants bush out to form a thick, stock-proof hedge.
LEACHING	The loss of soluble elements and compounds from soil in drainage waters to the aqueous environment, including both ground and surface waters. This applies especially to nitrate leaching. [R]; and soluble P losses from high P status soils.
LEY	Land temporarily sown to grass and then ploughed. [R]
LIGHT SOILS	See COARSE-TEXTURED SOILS.
LIVESTOCK UNIT	A unit used to compare or aggregate numbers of animals of different species or categories. Equivalences are defined on the feed requirements (or sometimes nutrient excretion). [R]
LOOSE-HOUSING	Animals have free access over the whole area of the building or pen. It is common for a deep layer of bedding (usually straw) to be spread over the floor, that is removed from the building, typically once or twice per winter, as FARMYARD MANURE. [R]
MACRO-PORE FLOW	Rapid vertical (and lateral) flow of water through ‘large’ diameter soil cracks, pores, earthworm burrows and old root channels. As the flow by-passes soil aggregates, it is less effective in leaching soluble nutrients from within the main soil matrix.
MAINTENANCE APPLICATION (of fertiliser)	Fertiliser application rate that when applied to soils with an optimum nutrient status will maintain this status over the longer-term by replacing the nutrients removed in harvested crops and in unavoidable losses, without increasing the amount stored in the soil.
MAINTENANCE DIET	Diet to provide the amount of food needed by an animal to keep it healthy and maintain a constant liveweight. [R]
MANUFACTURED (MINERAL) FERTILISER	Fertiliser manufactured by a chemical process or mined, as opposed to an organic material (manure) that contains carbon. [R]
MANURE	A general term to denote any organic material that supplies organic matter to soils together with plant nutrients, usually in lower concentrations compared with manufactured fertilisers. [R]
MARGINAL LAND	Land used for agriculture, but which has serious limitations (e.g. because of slope, soil depth, climate, wetness) that make it difficult to manage. As a result, crop yields and financial returns are generally lower than those provided by better quality land.
MATRIX FLOW	Predominantly vertical and relatively uniform flow of water through the soil, as opposed to more rapid MACRO-PORE FLOW that is confined to ‘large’ diameter soil cracks/pores etc. As there is greater contact with soil surfaces

	and finer pores, matrix flow is more effective at leaching soluble nutrients from the main soil matrix.
METHANE	CH_4. A greenhouse gas produced during anaerobic fermentation of organic matter, especially from the enteric fermentation in ruminants and storage of liquid manure. A constituent of biogas. [R]; methane has a global warming potential around 20-fold greater than carbon dioxide.
MINERALISATION	The transformation by microorganisms of organic compounds into organic compounds e.g. nitrogen/carbon in soils and stored manures. [R]
MINIMAL (REDUCED) CULTIVATION	Method of reduced (shallow) cultivation for tillage soils, using discs and tines, without ploughing and inverting the soil. As there is less disturbance of the soil, there is less mineralisation of soil organic matter and nitrogen, than following ploughing.
MONOGASTRIC	An animal with one simple stomach, such as pigs; as opposed to a RUMINANT. [R]
N	Nitrogen
NATURAL REGENERATION	Process by which vegetation is allowed to develop on a site from the seeds already present in the soil e.g. from weeds or grain shed by the previous crop.
NITRIFICATION	The transformation by bacteria of ammonium-N to nitrite and then to nitrate-N. An aerobic process that occurs in soils and during aeration of liquid manures. [R]
NITROUS OXIDE	N_2O. A greenhouse gas derived mainly from the DENITRIFICATION process. [R]; nitrous oxide has a global warming potential around 300-fold greater than carbon dioxide.
NSA	Nitrate Sensitive Area
NVZ	Nitrate Vulnerable Zone
ORGANIC FERTILISER	A fertiliser derived from organic origin, such as animal products (e.g. livestock manure, dried blood, hoof and bone meal), plant residues or human origin (e.g. sewage sludge). [R]
ORGANIC MANURE	See MANURE
OVERLAND FLOW	See RUNOFF
P	Phosphorus
P INDEX	ADAS Soil P Index; a method of expressing the results of laboratory soil extractable P analysis on a scale of 0 (low) to 9 (very high). The target status for most agricultural crops is Index 2 or 3.
P SATURATED SOIL	Soils in which the retention capacity of P is exceeded, resulting in the potential for LEACHING of P. [R]
PHASE FEEDING	The provision of different rations or diets to livestock at different stages of growth or performance, to match the ration closely to the requirements of the animal. [R]
PHYTASE	Type of enzyme that releases inorganic P from organic forms of P (phytate) in grain and thereby makes the P more available to animals.
POACHING	The puddling of soil as a result of trampling by livestock under wet conditions.
POLLUTION SWAPPING	Refers to pollution mitigation methods, where a method is effective at reducing losses of the target pollutant, but in doing so increases the loss of another pollutant e.g. where a reduction in nitrate leaching losses leads to increased nitrous oxide or ammonia emissions.
PREFERENTIAL FLOW	Broadly equivalent to MACRO-PORE FLOW.

RB209	“Reference Book 209. Fertiliser Recommendations for Agricultural and Horticultural Crops”, 7th Edition (2000), The Stationery Office, Norwich. Or “The Fertiliser Manual (RB209)”, 8th Edition (2010). The Stationery Office, Norwich.
REPLACEMENT RATE	The percentage of milking cows in a herd that are culled and replaced each year by younger animals; this is determined by the number of lactations that each cow has in the herd.
RESPONSE CURVE	The shape of a relationship between crop yield and the amount of (manufactured) fertiliser applied. Typically, this shows an initial steep increase in yield with increasing fertiliser rate, which gradually levels off and remains constant or declines at high rates of fertiliser use.
RILL EROSION	Soil erosion caused by surface runoff water collecting and concentrating into channels e.g. along depressions or tractor wheelings; the concentration of water into channels increases flow rates and the erosive force of the water. Further removal of sediment and deepening of the channel may lead to GULLY EROSION.
RILL FLOW	Flow of surface water in shallow to moderately deep erosion channels, as part of the process of RILL EROSION.
RIPARIAN	Located alongside a natural water course, such as by a stream or river.
ROUGH GRAZING	Poor quality grazing land, usually with natural or semi-natural vegetation.
RUMEN-DEGRADABLE PROTEIN	The proportion of protein in ruminant diets that is broken down in the rumen to liberate ammonia, which is utilised by other microorganisms in the rumen to synthesise microbial protein and is then digested in the small intestine.
RUMINANT	An animal that has a complex digestive system, including a four-part stomach. Includes cattle, sheep, goats and deer. [R]
RUNOFF	The flow of rainfall, irrigation water, liquid manures etc. from land; referred to as surface runoff where losses are from the soil surface. Runoff can cause pollution by transporting pollutants e.g. from manures to surface waters. [R]
SEDIMENT	Refers to soil particles washed into surface waters from agricultural land; such particles will settle onto the stream/river bed when the flow rate of the water is insufficient to keep them in suspension and can be important contributors to diffuse nutrient pollution, for example, from P adsorbed on their surfaces.
SHALLOW SOILS	Soils over chalk, limestone or other rock where the parent material is within 40 cm of the soil surface.
SHEET EROSION	Removal of a (uniform) thin layer of topsoil by raindrop splash and surface water runoff. Less visible than RILL or GULLY EROSION.
SHEET FLOW	Water accumulating on a slope and flowing as a thin sheet over the soil surface. May cause SHEET EROSION.
SHEET WASH	See SHEET FLOW
SLITTING	A mechanical soil treatment to penetrate shallow compacted/impermeable layers in grassland soils, by creating regular shallow slits in the upper topsoil, to improve surface water infiltration and root penetration.
SLUMPING	Process that can occur in sandy and silty soils, where raindrop impact and wetting causes the soil surface structure to collapse and a thin crust to develop that prevents surface water infiltration and increases RUNOFF. See CAPPING.
SLURRY	Mixture of faeces and urine produced by housed livestock that flows under gravity and can be pumped. [R]

SOAK-AWAY	Pit where unpolluted or slightly contaminated water is collected and allowed to soak into the surrounding ground.
SOIL AERATION	Process of increasing the porosity and permeability of a soil to allow greater entry of air and exchange with the atmosphere.
SOIL CAPPING	See CAPPING
SOIL COMPACTION	See COMPACTION
SOIL EROSION	See EROSION
SOIL ORGANIC MATTER	Collective term for the different forms of organic material in soil, including fresh plant residues, microbial biomass and more fully decomposed (relatively) stable humus.
SOIL STRUCTURE	The way in which individual particles comprising a soil (sand, silt, clay and organic matter) are organised into aggregates, with pores and channels between them.
SOLID MANURE	Manure from housed livestock that does not flow under gravity, cannot be pumped, but can be stacked in a heap. May include manure from cattle, pigs, poultry, horses, sheep and goats. [R]; usually includes bedding (e.g. straw, wood shavings etc.).
SOM	SOIL ORGANIC MATTER
SPIKING	A mechanical soil treatment to penetrate shallow compacted/impermeable layers in grassland soils, by creating many closely-spaced vertical holes, to improve surface water infiltration and root penetration.
SPRING TINE (harrow)	A lightweight cultivation implement, typically used for seedbed preparation, weeding crops, breaking-up capped soil or clearing moss and thatch from the base of grass swards.
STEADING	The main area of buildings and yards of a farm, traditionally adjoining the farm house.
STRIP GRAZING	A grazing system e.g. for cattle, in which the animals are given access to a limited area of fresh pasture (usually up to twice daily) by means of a moveable fence. Grazed strips are commonly 'back-fenced' (i.e. behind the cattle) to allow for regrowth of the grass. [R]
STRUCTURAL DAMAGE (of soil)	Physical damage to SOIL STRUCTURE, caused by livestock trampling or passage of farm machinery, particularly under wet conditions. Soil aggregates are broken down, leading to an increase in bulk density and reduced porosity, water infiltration, aeration and root penetration. See COMPACTION and POACHING.
SUBSOILING	A mechanical soil treatment to break up compacted/impermeable (usually deep) layers in a soil to improve water infiltration and root penetration. Achieved by drawing widely spaced tines through the soil, at the required depth, to produce a shattering effect.
SUCKLER COW	A cow that is allowed to rear its own calf before being used for beef production, rather than for milk production. [R]
SURFACE RUNOFF	See RUNOFF
SURFACE WATER	Water that flows in streams and rivers, natural lakes, wetlands and reservoirs constructed by humans. [R]
TILLAGE	General term for the process of soil cultivation.
TP	Total phosphorus
TRAMLINES	Accurately spaced, narrow pathways left in e.g. a cereal crop to provide wheel guide marks for tractors and machinery used in subsequent operations, e.g. fertiliser application, plant protection product application. [R]

TRANSPONDER	A wireless communications device that picks up and automatically responds to an incoming signal. Used in dairies, mounted in a collar on each cow, to automatically identify the particular animal and allow only that cow to access its allocated feed.
ULTRA-VIOLET LIGHT	A component of the spectrum of sunlight, which is harmful to organisms and accelerates the death of microorganisms, for example, when they are exposed on the soil surface.
UMBILICAL SPREADING SYSTEM	Liquid manure (slurry) is fed through a long hose to an applicator fitted directly on the rear of a tractor. The hose is supplied with liquid manure direct from the store or from a buffer tank by a pump. [R]
UNDERSOWN	Process of sowing a second crop into an already established crop, which develops as an understory and grows on after the main crop has been harvested. This avoids an interval of bare soil between crops and continued uptake of plant nutrients from the soil.
URINE PATCH	Localised area of grazed grassland that has received urine from (generally) a single urination and contains high concentrations of urea, which breaks down to form ammonium-N and following NITRIFICATION nitrate-N.
VOLATILISATION	The process by which AMMONIA gas is released from solution. [R] Refers to the loss of AMMONIA from urine and from MANURES during housing, storage and following land application.
VOLUNTEER (plants)	Plants that result from natural germination, as opposed to having been planted, including plants that re-occur in subsequent seasons following their harvest e.g. through germination of shed seed.
WATER MEADOWS	Low-lying grassland areas adjoining water courses, where the stream or river is allowed to naturally flood the fields during winter and the land is grazed during the drier summer period. Water levels may also be managed by a system of dams and sluices.
WATER TABLE	The level in a soil below which the ground is completely saturated with water.
WATERLOGGED SOIL	A soil that is saturated with water i.e. the pores are completely filled with water and air is excluded. [R]
WEANER	A piglet aged between 3 to 10 weeks that has been weaned from the sow's milk.

APPENDIX IV. REFERENCES

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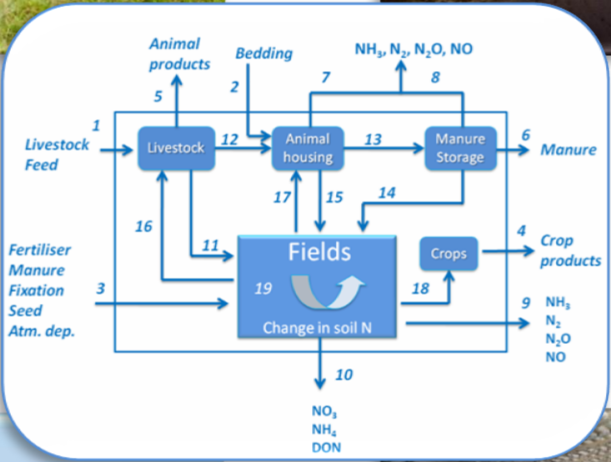
Exhibit 40

Options for Ammonia Mitigation

Guidance from the UNECE Task Force on Reactive Nitrogen



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Options for Ammonia Mitigation

Guidance from the UNECE Task Force on Reactive Nitrogen

Edited by: S. Bittman, M. Dedina, C.M. Howard, O. Oenema & M.A. Sutton

Task Force Reactive Nitrogen
Convention on Long Range Transboundary Air Pollution

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Preface

This document represents the culmination of a major effort to synthesize and update available knowledge on the control of ammonia emissions from agriculture to the atmosphere.

Under the Convention on Long-range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE), first national ceilings for emissions of ammonia were established under the Gothenburg Protocol in 1999. At the same time, the Protocol included an annex of measures for the control of ammonia emissions (known as Annex IX).

To provide support to the Parties of the CLRTAP in meeting these ceilings and Annex IX, the 17th Session of the Executive Body of the Convention agreed to establish an 'Ammonia Guidance Document'[1] .The importance of this document was further highlighted in the Protocol itself, where Article 3, paragraph 8 (b) requires each Party within the geographical scope of the European Monitoring and Evaluation Programme (EMEP) to *"Apply, where it considers it appropriate, best available techniques for preventing and reducing ammonia emissions, as listed in Guidance Document V* [the Ammonia Guidance Document] *adopted by the Executive Body at its seventeenth session (decision 1999/1) and any amendments thereto."* The Ammonia Guidance Document is thus a legally established benchmark against which to consider implementation of techniques for reducing ammonia emissions in the Gothenburg Protocol.

The first revision of the Ammonia Guidance Document was completed in 2007 by the UNECE Ammonia Expert Group (ECE/EB.AIR/WG.5/2007/13). This first revision came shortly after the entry into force of the Gothenburg Protocol of 2005. Since that time, substantial further information on ammonia mitigation methods, their costs, benefits and practicalities, has become available. Also, a major revision of the Gothenburg Protocol itself has been accomplished, with new emissions ceilings and provisions adopted in May 2012 (Executive Body decision 2012/1). In support of these developments, and in accordance with the Work Plan agreed by the Executive Body, the present (second) revision of the Ammonia Guidance Document has been prepared.

This revised Ammonia Guidance Document has benefited from the contributions of many experts. Following the earlier contribution of the Ammonia Expert Group, the importance of developing a broader view on nitrogen air pollution was recognized by the Executive Body, leading to its establishment in 2007 of the Task Force on Reactive Nitrogen (TFRN). The TFRN has "the long-term goal of developing technical and scientific information, and options which can be used for strategy development across the UNECE to encourage coordination of air pollution policies on nitrogen in the context of the nitrogen cycle and which may be used by other bodies outside the Convention in consideration of other control measures" (www.clrtap-tfrn.org). Within this broader perspective, the TFRN works through a series of Expert Panels, including the Expert Panel on Mitigation of Agricultural Nitrogen (EPMAN), which has taken up the lead on the second revision of the Ammonia Guidance Document.

This second revised Ammonia Guidance Document has been adopted by the Executive Body (decision 2012/11), being released as document ECE/EB.AIR/120. The TFRN agreed at its meeting in St. Petersburg to publish the work as an accessible document to encourage wider use and both English and Russian versions will be printed. The Ammonia Guidance Document can also be downloaded from the website of the TFRN (www.clrtap-tfrn.org). As part of the dissemination process, a German language version of the present document has also been prepared, a link to which is posted on the TFRN website.

While the formal reports of the TFRN to the UNECE Working Group on Strategies and Review (WGSR) and to the Executive Body are anonymous, the present publication therefore strives to recognize all the author contributors to the revision process. As will be seen, the present revision of the Ammonia Guidance Document includes co-authors from across the UNECE region, with contributions from 15 countries, as well as the EMEP Centre for Integrated Assessment Modelling (CIAM). We here express our gratitude for the many inputs received, as well as the inputs from many peer reviewers, stakeholder reviews and national comments. We

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[1] *Officially titled the "Guidance Document for Preventing and Abating Ammonia Emissions from Agricultural Sources" and also listed as Guidance Document V, Executive Body decision 1999/1.*

particularly, thank the UNECE Secretariat for their support though the process, especially Fransizka Ilg, Krzysztof Olendrzynski and Albena Karadjova.

The Ammonia Guidance Document is meant as a state-of-the-art reference document for preventing and abating ammonia emissions from agricultural sources, to be used primarily by policy makers, those in industry and scientists. It shows the various possible measures in the whole ‘animal feeding – animal housing – manure management chain’. It discusses the effectiveness of the measures as well as the economic cost of the measures. Additional information on the economic costs of emission abatement measures can be found in the TFRN publication “Economic costs of ammonia emissions abatement” (Reis et al., 2014).

Lastly, the 2012 revision of the Gothenburg Protocol reiterated the commitment of the Parties to the CLRTAP to establish a national “advisory code of good agricultural practice to control ammonia emissions” (Gothenburg Protocol Annex IX, paragraph 3). In support of this requirement, the TFRN, working through EPMAN, is currently preparing a revision of the UNECE “Framework code for good agricultural practices for reducing emission of ammonia" (EB.AIR/WG.5/2001/7). The emphasis of this revised Framework Code will be on practical approaches, offering a framework to aid policy makers and extension services in refining and publishing their own national ammonia codes, to be used by extension services and farmers.

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Co-chairs of the UNECE Task Force on Reactive Nitrogen.

Clare M. Howard
Task Force Co-ordinator, TFRN.

Edinburgh, Wageningen and Aarhus, February 2014

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[2] *Co-chair until 2013*

[3] *Co-chair from 2014*

Executive Summary

O. Oenema, M.A. Sutton, S. Bittman, M. Dedina & C.M. Howard

1. The purpose of this document is to provide guidance to the Parties to the United Nations Economic Commission for Europe (ECE) Convention on Long-range Transboundary Air Pollution in identifying ammonia (NH_3) control measures for reducing emissions from agriculture, as indicated in annex IX to the Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol).

2. This document summarizes:

(a) The current knowledge of NH_3 emission abatement techniques and strategies;

(b) The scientific and technical background of the techniques and strategies;

(c) The economic cost of the techniques, in terms of euros per kilogramme (kg) of NH_3 abated;

(d) Any limitation or constraint with respect to the applicability of the techniques.

3. The document addresses NH_3 emission abatement measures in the following areas:

(a) Nitrogen (N) management, taking into account the whole N cycle;

(b) Livestock feeding strategies;

(c) Animal housing techniques;

(d) Manure storage techniques;

(e) Manure application techniques;

(f) Fertilizer application techniques;

(g) Other measures related to agricultural N;

(h) Measures related to non-agricultural and stationary sources.

4. **Nitrogen management** is an integral measure to decrease N losses. Nitrogen management is based on the premise that decreasing the nitrogen surplus (Nsurplus) and increasing N use efficiency (NUE) contribute to abatement of NH_3 emissions. On mixed livestock farms, between 10% and 40% of the Nsurplus is related to NH_3 emissions. Nitrogen management also aims to identify and prevent pollution swapping between different N compounds and environmental compartments. Establishing an N input-output balance at the farm level is a prerequisite for optimizing N management in an integral way.

5. The cost of establishing a farm N balance is in the range of €200–€500 per farm per year. (The farm balance refers to an accounting for all N inputs such as feed, fertilizer, etc., and all N outputs in products.) Note that costs associated with education, promotion and start-up are not considered here. The cost of increasing NUE through improving management are in the range of -€1.0–€1.0 per kg N saved. The possible savings are related to less cost for fertilizer and increased crop quality. The possible costs are related to increased cost for advisory services and soil, crop, feed and manure analyses. The economic cost of possible investments in techniques are not included here, but discussed with the other provisions. Table ES1 lists indicative ranges for NUE and the Nsurplus of the input-output balance of different farming systems. These ranges serve as rough guidance; they can be made more farm and country specific. NUE should be managed in concert with overall nutrient efficiencies and other factors, such as pest control.

Table ES1

Indicative ranges for target Nsurplus and NUE as a function of farming system, crop species and animal categories

Farming systems	*Species/catagories*	*NUE (kg/kg)*	*Nsurplus (kg/ha/yr)*	*Comments*
Specialized cropping systems	Arable crops	0.6–0.9	0–50	Cereals have high, root crops low, NUE
	Vegetables	0.4–0.8	50–100	Leafy vegetables have low NUE
	Fruits	0.6–0.9	0–50	
Grassland-based ruminant systems	Dairy cattle	0.3–0.5	100–150	High milk yield, high NUE; low stocking density, low Nsurplus
	Beef cattle	0.2–0.4	50–150	Veal production, high NUE; 2-year-old beef cattle, low NUE
	Sheep and goats	0.2–0.3	50–150	
Mixed crop-animal systems	Dairy cattle	0.4–0.6	50–150	High milk yield, high NUE; concentrate feeding, high NUE
	Beef cattle	0.3–0.5	50–150	
	Pigs	0.3–0.6	50–150	
	Poultry	0.3–0.6	50–150	
	Other animals	0.3–0.6	50–150	
Landless systems	Dairy cattle	0.8–0.9	n.a.[a]	N Output via milk, animals, manure + N-loss ~equals N input; Nsurplus is gaseous N losses from housing and storage
	Beef cattle	0.8–0.9	n.a.[a]	
	Pigs	0.7–0.9	n.a.[a]	
	Poultry	0.6–0.9	n.a.[a]	
	Other animals	0.7–0.9	n.a.[a]	

[a] Not applicable, as these farms have essentially no land. However, the Nsurplus can be expressed in kg per farm per year. In the case that all animal products, including animal manure and all residues and wastes, are exported, the target Nsurplus can be between 0 and 1,000 kg per farm per year, depending on farm size and gaseous N losses.

6. **Livestock feeding strategies** decrease NH_3 emissions from manure in both housing and storage, and following application to land. Livestock feeding strategies are more difficult to apply to grazing animals, but emissions from pastures are low and grazing itself is essentially a category 1 measure.[4] Livestock feeding strategies are implemented through (a) phase feeding, (b) low-protein feeding, with or without supplementation of specific synthetic amino acids and ruminal by-pass protein, (c) increasing the non-starch polysaccharide content of the feed, and (d) supplementation of pH-lowering substances, such as benzoic acid. Phase feeding is an effective and economically attractive measure even if one that requires additional installations. Young animals and high-productive animals require more protein concentration than older, less-productive animals. Combined NH_3 emissions for all farm sources decrease roughly by 10% when mean protein content decreases by 10 grams (g) per kg (1%) in the diet. The economic cost of the livestock feeding strategies depends on the

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[4] See paras. 18 and 19 for a description of the various categories.

Table ES2

Indicative target protein levels (%) of dry feed with a standard dry matter content of 88% for housed animals as a function of animal category and for different ambition levels

	Mean crude protein content of the animal feed (%)[a]		
Animal type	*Low ambition*	*Medium ambition*	*High ambition*
Cattle			
Dairy cattle, early lactation (> 30 kg/day)	17–18	16–17	15–16
Dairy cattle, early lactation (< 30 kg/day)	16–17	15–16	14–15
Dairy cattle, late lactation	15–16	14–15	12–14
Replacement cattle (young cattle)	14–16	13–14	12–13
Veal	20–22	19–20	17–19
Beef < 3 months	17–18	16–17	15–16
Beef > 6 months	14–15	13–14	12–13
Pigs			
Sows, gestation	15–16	14–15	13–14
Sows, lactation	17–18	16–17	15–16
Weaner, <10 kg	21–22	20–21	19–20
Piglet, 10–25 kg	19–20	18–19	17–18
Fattening pig, 25–50 kg	17–18	16–17	15–16
Fattening pig, 50–110 kg	15–16	14–15	13–14
Fattening pigs, >110 kg	13–14	12–13	11–12
Chickens			
Chicken, broilers, starter	22–23	21–22	20–21
Chicken, broilers, growers	21–22	20–21	19–20
Chicken, broilers, finishers	20–21	19–20	18–19
Chicken, layers, 18–40 weeks	17–18	16–17	15–16
Chicken, layers, > 40 weeks	16–17	15–16	14–15
Turkeys			
Turkeys, < 4 weeks	26–27	25–26	24–25
Turkeys, 5–8 weeks	24–25	23–24	22–23
Turkeys, 9–12 weeks	21–22	20–21	19–20
Turkeys, 13–16 weeks	18–19	17–18	16–17
Turkeys, > 16 weeks	16–17	15–16	14–15

Note: A decrease of the protein content in the feed by 1% may decrease the total NH_3 emissions from all manure sources by 10%.

[a] With adequately balanced and optimal digestible amino acid supply.

cost of the feed ingredients and the possibilities of adjusting these ingredients, based on availability, to optimal proportions. The reference here is the mean current practice, which varies considerably across countries and animal performance, although the effects in the latter case are more evident to producers. The cost of the diet manipulations are in the range of -€10–€10 per 1,000 kg of feed, depending on market conditions for feed ingredients and the cost of the synthetic amino acids. Hence, in some years there are benefits while in other years there are costs associated with changes in diets. Table ES2 summarizes possible targets for lowering protein values, maintaining production efficiencies for each animal category (see also annex II). Note that the economic costs increase as the ambitions to decrease the mean protein content increase from low to high.

7. For animal housing, abating NH_3 emissions is based on one or more of the following principles:

(a) Decreasing the surface area fouled by manure;

(b) Rapid removal of urine; rapid separation of faeces and urine;

(c) Decreasing the air velocity and temperature above the manure;

(d) Reducing the pH and temperature of the manure;

(e) Drying manure (especially poultry litter);

(f) Removing (scrubbing) NH_3 from exhaust air;

(g) Increasing grazing time.

8. All principles have been applied in category 1 (i.e., scientifically sound and practically proven) techniques. Different animal categories require different housing systems and environmental conditions, hence different techniques. Because of their different requirements and housing, there are different provisions according to animal categories. The references used are the most conventional housing systems, without techniques for abating NH_3 emissions. The costs of techniques used to lower NH_3 emissions from housing are related to: (a) depreciation of investments; (b) return on investments; (c) energy; and (d) operation and maintenance. In addition to costs, there are benefits related to increasing animal health and performance. These benefits are difficult to quantify and have not always been included in the total cost estimate. The economic costs vary because of different techniques/variants and farms sizes; techniques for cattle housing are still in development. Table ES3 presents an overview of the emission reduction and economic cost for the major animal categories.

Table ES3

Ammonia emission reduction techniques for animal housing, their emission reduction levels and associated costs

Category	*Emission reduction compared with the reference (%)* [a]	*Extra cost (€/kg NH_3-N reduced)*
Existing pig and poultry housing on farms with > 2,000 fattening pigs or > 750 sows or > 40,000 poultry	20	0–3
New or largely rebuilt cattle housing	0–70	1–20
New or largely rebuilt pig housing	20–90	1–20
New and largely rebuilt broiler housing	20–90	1–15
New and largely rebuilt layer housing	20–90	1–9
New and largely rebuilt animal housing on farms for animals other than those already listed in this table	0–90	1–20

[a] The references are specified further on in the Guidance document.

9. For **manure storages**, abating NH_3 emissions is based on one or more of the following principles: (a) decreasing the surface area where emissions can take place, i.e., through covering of the storage, encouraging crusting and increasing the depth of storages; (b) decreasing the source strength of the emitting surface, i.e., through lowering the pH and ammonium (NH_4) concentration; and (c) minimizing disturbances such as aeration. All principles have been applied in category 1 (i.e., scientifically sound and practically proven) techniques. These principles are generally applicable to slurry storages and manure (dung) storage. However,

the practical feasibility of implementing the principles are larger for slurry storages than for manure (dung) storages. The reference here is the uncovered slurry store without crust and uncovered solid manure heap.

10. The costs of techniques used to lower NH_3 emissions from storages are related to: (a) depreciation of investments; (b) return on investments; and (c) maintenance. Here, a summary is provided of the total costs, in terms of euros per kg of ammonia-nitrogen (NH_3-N) saved (table ES4). In addition to costs, there are benefits related to decreased odour emissions, decreased rainwater accumulation and increased safety (no open pits); some of these benefits are difficult to quantify and therefore have not been included here. Ranges of costs relate to different techniques/variants and farm size. Note that the cost of the storage system itself is not included in the cost estimates of table ES4. Some covers can only be implemented when new storages are built. Manure processing, such as separation, composting and digestion, have implications for the total losses during "storage".

Table ES4

Ammonia emission reduction techniques for manure storages, their emission reduction levels and associated costs

Techniques	*Emission reduction (%)*	*Cost (€ per m^3 per year)*	*Cost (€ per kg NH_3-N saved)*
Tight lid	> 80	2–4	1–2.5
Plastic cover	> 60	1.5–3	0.5–1.3
Floating cover	> 40	1.5–3[*)]	0.3–5[a]

[a] Not including crust; crusts form naturally on some manures and have no cost, but are difficult to predict.

11. **Low-emission manure application** is based on one or more of the following principles: (a) decreasing the surface area where emissions can take place, i.e., through band application, injection or incorporation; (b) decreasing the time that emissions can take place, i.e., through rapid incorporation of manure into the soil, immediate irrigation or rapid infiltration; and (c) decreasing the source strength of the emitting surface, i.e., through lowering the pH and NH_4 concentration of the manure (through dilution). All principles have been applied in category 1 (i.e., scientifically sound and practically proven) techniques. These principles are generally applicable to slurry and solid manure application. However, abatement techniques are more applicable and effective for slurry than for solid manures. For solid manure, the most feasible technique is rapid incorporation into the soil and immediate irrigation. The reference here is the broadcast spreading of slurry and solid manure. A fourth principle, applying when volatilization potential is low, such as under low temperature and wind conditions, is considered category 2[5] because it requires a method of validation. The costs of techniques used to lower NH_3 emissions from application are related to: (a) depreciation of investments costs of the applicator; (b) return on investments; (c) added tractor costs and labour; and (d) operation and maintenance.

12. Here, a summary is provided of the total costs, in terms of euros per kg NH_3-N saved (table ES5). The co-benefits relate to decreased odour emissions and biodiversity loss, and increased palatability of herbage, uniformity of application and consistency of crop response to manure. Some of these benefits are difficult to quantify and therefore have not all been included in the cost estimations. Ranges of costs relate to the NH_4 content of the slurry/manure; the higher the NH_4 content, the lower the abatement cost. Mean costs are likely in the lower half of the range, especially when application is done by contractors, on large farms or with shared equipment.

13. For **application of urea- and ammonium-based fertilizers**, abating emissions is based on one or more of the following principles: (a) decreasing the surface area where emissions can take place, i.e., through band application, injection, incorporation (but note that rapid increase in pH in concentrated bands of urea, especially where there is high crop residue, may lead to high emissions due to rise in pH); (b) decreasing the time that emissions can take place, i.e., through rapid incorporation of fertilizers into the soil or via irrigation; (c) decreasing the source strength of the emitting surface, i.e., through urease inhibitors, blending and

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[5] See paras. 18 and 19 for a description of the various categories.

acidifying substances; and (d) a ban on their use (as in the case of ammonium (bi)carbonate). All principles have been applied in category 1 (i.e., scientifically sound and practically proven) techniques. The reference here is the broadcast application of the urea- and ammonium-based fertilizers.

Table ES5

Ammonia emission reduction techniques for manure application, their emission reduction levels and associated costs

Manure type	*Application techniques*	*Emission reduction (%)*	*Cost (€ per kg NH_3-N saved)*
Slurry	Injection	> 60	-0.5–1.5
	Shallow injection	> 60	-0.5–1.5
	Trailing shoe,	> 30	-0.5–1.5
	Band application	> 30	-0.5–1.5
	Dilution	> 30	-0.5–1.0
	Management systems	> 30	0.0–2.0
	Direct incorporation following surface application	> 30	-0.5–2.0
Solid manure	Direct incorporation	> 30	-0.5–2.0

14. The costs of techniques used to lower NH_3 emissions from fertilizers are related to: (a) depreciation of investment costs of the applicator; (b) return on investments; (c) use of heavier tractors and more labour time; and (c) maintenance. Here, a summary is provided of the total costs, in terms of euros per kg NH_3-N saved (table ES6). The possible benefits relate to decreased fertilizer costs, decreased application costs in a combined seeding and fertilizing system and decreased biodiversity loss. These benefits are difficult to quantify and have not all been included. Ranges of costs relate to the farm size (economics of scale), soil conditions and climate (high emission reduction in relatively dry conditions). Mean costs are likely in the lower half of the range when application is done by contractors or low emitting fertilizers are substituted.

Table ES6

Ammonia emission reduction techniques for application of urea- and ammonium-based fertilizers, their emission reduction levels and associated costs

Fertilizer type	*Application techniques*	*Emission reduction (%)*	*Cost (€ per kg NH_3-N saved)*
Urea	Injection	> 80	-0.5–1
	Urease inhibitors	> 30	-0.5–2
	Incorporation following surface application	> 50	-0.5–2
	Surface spreading with irrigation	> 40	-0.5–1
Ammonium carbonate	Ban	~100	-1–2
Ammonium-based fertilizers	Injection	> 80	0–4
	Incorporation following surface application	> 50	0–4
	Surface spreading with irrigation	> 40	0–4

Chapter 1

Introduction

O. Oenema, M.A. Sutton, S. Bittman, M. Dedina & C.M. Howard

15. The purpose of this document is to provide guidance to the Parties to the United Nations Economic Commission for Europe (ECE) Convention on Long-range Transboundary Air Pollution in identifying ammonia (NH_3) control measures for reducing emissions from agricultural sources, taking account of the whole nitrogen (N) cycle. This guidance document will facilitate the implementation of the basic obligations of the Convention's Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol) mentioned in its article 3, as regards NH_3 emissions, and, more specifically, will contribute to the effective implementation of the measures listed in annex IX, and to achieving the national NH_3 emission ceilings listed in annex II, table 3 of the Protocol.

16. The document addresses the abatement of NH_3 emissions produced by agricultural sources. Agriculture is the major source of NH_3, chiefly from livestock excreta in livestock housing, during manure storage, processing, treatment and application to land, and from excreta from animals at pasture. Emissions also occur from inorganic N fertilizers following their application to land and from N-rich crops and crop residues, including grass silage. Emissions can be reduced through abatement measures in all the above areas but with varying degrees of practicality, efficacy and costs.

17. The first version of the present Guidance document (see EB.AIR/1999/2) provided general guidance on the abatement of NH_3 emissions. This original version was revised in 2007 (ECE/EB.AIR/WG.5/2007/13). The current version is further revised and reflects the state of scientific and technological development at the start of 2012.

18. In this document, strategies and techniques for the abatement of NH_3 emissions and N losses are grouped into three categories:

(a) **Category 1 techniques and strategies**: These are well researched, considered to be practical or potentially practical, and there are quantitative data on their abatement efficiency, at least on the experimental scale;

(b) **Category 2 techniques and strategies**: These are promising, but research on them is at present inadequate, or it will always be difficult to generally quantify their abatement efficiency. This does not mean that they cannot be used as part of an NH_3 abatement strategy, depending on local circumstances;

(c) **Category 3 techniques and strategies**: These have not yet been shown to be effective or are likely to be excluded on practical grounds.

19. Based on the available research, category 1 techniques can be considered as already verified for use in abatement strategies. Category 2 and category 3 techniques may also be used in abatement strategies. However, for these categories independent verification should be provided by Parties using them in order to demonstrate the reductions in NH_3 emissions that they report. It should be noted that the cost of a technique is not considered for the classification. Information on costs is provided to support decisions on the use of the techniques.

20. Separate guidance has also been prepared, at the European Union (EU) level, under the Integrated Pollution Prevention and Control (IPPC) Directive[6] (superseded in November 2011 by the Industrial Emissions Directive)[7] to reduce a range of polluting emissions from large pig and poultry units. The *Reference Document on Best Available Techniques for Intensive Rearing of Poultry and Pigs*[8] is currently under revision. There is only partial overlap between this best available techniques (BAT) EU reference document (or BREF) and the present guidance document, since in it BAT has only been defined for the pig and poultry sectors, and has not been defined for cattle, sheep or other livestock, nor for the land application of manures or fertilizers. The current document is more inclusive for farms and sectors because it addresses also NH_3 emissions from manure and fertilizer application to land and various other sources.

21. Options for NH_3 reduction at the various stages of livestock manure production and handling are interdependent, and combinations of measures are not simply additive in terms of their combined emission reduction. Controlling emissions from applications of manures to land is particularly important, because these are generally a large component of total livestock emissions and because land application is the last stage of manure handling. Without abatement at this stage, much of the benefit of abating during housing and storage, which is often more costly, may be lost. Likewise, controlling emissions from land application will have less benefit for total farm losses and N-use efficiency if large losses occur in barns and storages. Reduction in N-excretion rates from livestock has the most direct effect on emissions and has been added to this document. Because of this interdependency, Parties should as far as possible exploit models where the overall mass flow of N is assessed, in order to optimize their abatement strategies. Therefore, the whole farm context, including animal feeding, has also been added to this document.

22. Many measures may incur both capital and operational costs (see table 1 (a) and (b)). In addition to theoretical calculations based on capital and operating expenditure, actual data on costs (e.g., as charged by contractors) should be used where available. In addition to calculating the direct costs, the benefits of measures should as far as possible be calculated. In many cases, the combined benefits to the farmer (e.g., reduced mineral fertilizer need, improved agronomic flexibility, reduced emissions of other pollutants, less complaints due to odour) may outweigh the costs. Comparison of the net cost to the farmer (i.e., cost minus benefit) with other environmental benefits (e.g., improved air, water quality and soil quality, reduced biodiversity loss, reduced perturbation of climate) is beyond the scope of this document.

23. The costs of the techniques will vary from country to country. It should be noted that, due to economies of scale, some of the abatement techniques may be more cost-effective on large farms than on small farms. This is especially so when an abatement technique requires the purchase of capital equipment, e.g., reduced-emission slurry applicators. In such cases, the unit costs decrease as the volumes of manure increase. A greater cost burden for smaller farms may also be the case for immediate incorporation of manures. Both for slurry application and manure incorporation, the costs for small farms will often be reduced by spreading the costs of the equipment over several farms through use of contractors with access to suitable equipment, sometimes locally designed and built. Therefore the upper range of costs may also be reduced by focusing mitigation efforts on medium and large farms.

24. Wherever possible, techniques listed in this document are clearly defined and assessed against a "reference" or unabated situation. The reference situation, against which percentage emission reduction is calculated is defined at the beginning of each chapter. In most cases the reference is the practice or design that is the most commonly practised technique presently found on commercial farms in the ECE region and is used to construct baseline inventories.

25. When introducing new measures, there is often a cost associated with education, promotion and start-up which are not considered here. In most cases, there are substantial co-benefits arising from the measures, not included in the costing, which will improve the overall well-being of farming operations and of the public. An example is the reduction of odour, resulting from reduced emissions, which will benefit the public (and may even improve tourism) and farmers and their families. The secondary cost savings are also not counted: for example, reduced pollution and energy use from fertilizer manufacturing plants due to better conservation of NH_3 on farms. Some measures (e.g., manure injection, covers for farm-yard manure (FYM),

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[6] Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 concerning integrated pollution prevention and control.

[7] Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control).

[8] Available from http://eippcb.jrc.es/reference/irpp.html (accessed on 24 May 2013).

acidification, scrubbing exhaust air) reduce the risk of contaminating waterways with N, other nutrients, pathogens and other contaminants.

Table 1 (a)

Capital costs (capital expenditure (CAPEX))[9]

Consideration	*Notes*
Capital for fixed equipment or machinery	Fixed equipment includes building, installations, conversions of buildings, feed storage bins, or manure storage covers. Machinery includes feed distribution augers, field equipment for manure application or equipment for manure treatment, etc.
Labour cost of installation	Use contract charges if these are normal. If farm staff are normally used to install the conversion, employed staff should be rated at typical hourly rates. Farmers' input should be charged at the opportunity cost.
Grants	Subtract the value of capital grants available to farmers.

Table 1 (b)

Annual costs (operational expenditure (OPEX)): the annual cost associated with the introduction of a technique

Consideration	*Notes*
Annualized cost of capital should be calculated over the life of the investment	Use standard formula. The term will depend on the economic life. Conversions need to take account of remaining life of original facility.
Repairs associated with the investment should be calculated	A certain percentage of the capital costs.
Changes in labour costs	Additional hours at x cost per hour.
Fuel and energy costs	Additional power requirements may need to be taken into account.
Changes in livestock performance	Changes in diets or housing can affect performance, with cost implications.
Cost savings and production benefits	The introduction of techniques will often result in cost savings for the farmer. These should be quantified as far as possible. Separate note should be taken of the avoidance of fines for pollution in costing benefits.

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[9] CAPEX (new) means the investment costs in new build situations, in contrast with CAPEX (retrofit) meaning rebuilding or renovation of buildings.

Chapter 2

Livestock production and developments

O. Oenema, S. Bittman, M. Dedina & M.A. Sutton

26. Livestock excreta in livestock housing, during manure storage, processing, treatment and application to land, and from excreta from animals at pasture are the main sources of NH_3 emissions in most ECE countries. Therefore, it is imperative to provide some brief information here on the livestock sector.

27. The livestock sector is an important contributor to the global food and agricultural economy and to human nutrition and culture, accounting for 40% of the value of world agricultural output and providing 10%–15% of total food calories and one quarter of dietary protein. In most of the developing country regions it is the fastest growing segment of the agricultural sector. The livestock sector is expected to provide safe and plentiful food for growing urban populations and livelihoods for almost 1 billion poor producers, while at the same time it enables the exploitation of non-arable lands, provides food security against crop failure for subsistence farmers, utilizes food wastes and field losses or residues, and even provides fuels and concentrates and recirculates farm nutrients, as well as global public goods related to food security, environmental sustainability and public health (Geers and Madec, 2006; FAO, 2009; Steinfeld and others, 2010).

28. While livestock provides various useful functions to society and the global demand for dairy, meat and egg products is slated to continue to increase in the coming decades, there is also increasing pressure on (intensive) livestock production systems to become more environmentally friendly. The livestock sector is a major land user globally and has been implicated in deforestation and biodiversity loss (Steinfeld and others, 2006; FAO, 2009; Steinfeld and others, 2010). It is also a major user of fresh water, mainly through animal feed production, while freshwater resources are becoming scarce in some areas. Livestock production is a main source of atmospheric NH_3 and the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). The emissions of NH_3 mainly originate from the N in manure of animals. Emissions of NH_3 from livestock production are related to the type, number and genetic potential of the animals, the feeding and management of the animals and the technology of animal housing and manure management (Bouwman and others, 1997; Steinfeld and others, 2006; O. Oenema and others, 2008). Livestock dominate the requirement for reactive N in Europe. For example, the *European Nitrogen Assessment* has estimated that 85% of harvested N goes to feed livestock, while only 15% feeds people directly (Sutton and others, 2011).

29. Livestock production systems can broadly be classified into: (a) grazing systems; (b) mixed systems; and (c) fully confined landless or industrial systems (e.g., Seré, Steinfeld and Groenewold, 1996). Grazing systems are entirely land-based systems, with stocking rates at less than one or two livestock unit per hectare (ha), depending on grassland productivity. In mixed systems a significant part of the value of production comes from activities other than animal production, while part of the animal feed is often imported. Industrial systems have stocking rates greater than 10 livestock units per hectare and they depend primarily on outside supplies of feed, energy and other inputs. In industrial systems, 0%–10% of the dry matter fed to animals is produced on the farm. Relevant indicators for livestock production systems are animal density in animal units (AU) per hectare (AU/ha) and kilograms milk or meat per hectare per year (kg/ha/year). A common and useful indicator for the pressure on the environment is the total N or P excretion of the livestock per hectare per year (e.g., Menzi and others, 2010).

30. In each livestock category, a distinction can be made between conventional and organic farming. Further, there is often a distinction between intensive and extensive systems. Intensive livestock production systems are characterized by a high output of meat, milk, and eggs per unit of agricultural land and per unit of stock (i.e., livestock unit), which usually coincides with a high stocking density per unit of agricultural land. This is generally achieved by high efficiency in converting animal feed into animal products. Because of their capacity to rapidly respond to a growing demand for low-cost animal products, intensive livestock production systems now account for a dominant share of the global pork, poultry meat and egg production (respectively, 56%, 72% and 61%) and a significant share of milk production (Steinfeld and others, 2006; FAO, 2009).

31. Traditionally, most animal products consumed by humans were produced locally using locally produced animal feeds. Increasingly, many animal products consumed by humans in urban areas are produced using animal feeds imported from outside the animal production areas. This holds true especially for pig and poultry products. Thereby, areas of animal feed production and pig and poultry production become increasingly disconnected from the site of animal product consumption. This disconnection has been made possible through the development of efficient transport infrastructure and the relatively low price of fossil energy; the shipment of concentrated feed is cheap relative to other production costs. Transportation of meat and egg products has also become cheaper. However, the uncoupling of animal feed production from animal production has major consequences for the proper reuse and management of animal manure (FAO, 2009; Steinfeld and others, 2010 and references therein).

32. Increasingly, production chains are organized and regionally clustered in order to minimize production, processing and delivery costs. Animal feed is the major input to livestock production, followed by labour, energy, water and services. Input costs vary substantially from place to place within countries as well as across countries and continents. Access to technology, labour and know-how is also unevenly distributed, as is the ability to respond to changing environments and to market changes. There are also institutional and cultural patterns that further affect production costs, access to technologies and transaction costs. The combination of these factors determines that livestock production systems become larger, more specialized, and more intensive (FAO, 2009; Steinfeld and others, 2010).

33. Livestock production systems are dynamic systems because of continuous developments and changes in technology, markets, transport and logistics. Increasingly, livestock products are becoming “global commodities”, and livestock production systems are operating in an “open”, highly competitive, global market. These developments are facilitated by the increasing demand for low-cost animal products because of the increasing urban population and the increasing consumption of animal products per capita, although there are large economic, regional and continental differences. The additional demand for livestock products is concentrated in urban centres (FAO, 2009; Steinfeld and others, 2010).

34. The rapid developments in livestock production systems have a strong effect on the emissions of NH_3, N_2O and CH_4 from these systems to the atmosphere and of the leaching and run-off of N to waters. Emission abatement strategies have to take such developments into account and to anticipate new developments, so as to make these strategies effective and efficient in the future.

Chapter

3

Nitrogen management, taking account of the whole nitrogen cycle

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35. Management is often called the "fourth production factor", in addition to land, labour and capital (techniques). Its importance for the economic and environmental performance of agricultural is enormous. Management is commonly defined as "a coherent set of activities to achieve objectives". Nitrogen management can be defined as "a coherent set of activities related to the handling and allocation of N on farms to achieve agronomic and environmental/ecological objectives" (e.g., O. Oenema and Pietrzak, 2002). The agronomic objectives relate to crop yield and quality, and animal performance in the context of animal welfare. The environmental/ecological objectives relate to minimizing N losses from agriculture. "Taking account of the whole N cycle" emphasizes the need to consider all aspects of N cycling, also in "NH_3 emissions abatement", to circumvent "pollution swapping". Although not considered here, other pollutants and impacts must also be avoided. Nitrogen management can be considered as the "software" and "org-ware", while the techniques may be considered as the "hardware" of N emissions abatement. Hence, N management has to be considered in conjunction with the techniques used.

36. Nitrogen management varies greatly across the ECE region, and NH_3 emissions will vary accordingly. In general, emissions of N tend to decrease when:

(a) All N sources on the farm are fully considered in a coherent whole-farm perspective and a whole N-cycle perspective;

(b) All N sources are stored and handled properly;

(c) Amounts of N used are strictly according to the needs of growing plants and animals;

(d) N sources are used in a timely manner, using the appropriate techniques, in the appropriate amounts and appropriate place;

(e) All possible N-loss pathways are considered in a coherent manner.

Supplementary information about "N management, taking account of the whole N cycle" is provided in annex I.

37. *Reference situation*: The reference is a farm situation without N management planning and without use of N balances. Because of intrinsic differences in N cycling, a distinction has to be made between different farming systems, such as:

(a) Specialized crop producing farms, further divided into:

  (i) Arable crops;

  (ii) Vegetables;

  (iii) Fruits;

(b) Grassland-based ruminant production farms, further divided into:
    (i) Dairy cattle;
    (ii) Beef cattle;
    (iii) Sheep and/or goats;
    (iv) Other animals (buffalo, bison, deer, etc.);
(c) Mixed crop-animal systems, with as dominant animal:
    (i) Dairy cattle;
    (ii) Beef cattle;
    (iii) Pigs;
    (iv) Poultry;
    (v) Other animals;
(d) Specialized, landless, systems with:
    (i) Dairy cattle;
    (ii) Beef cattle;
    (iii) Pigs;
    (iv) Poultry;
    (v) Other animals.

Category 1 strategies

38. Implementing effective N management at the farm level is an effective strategy to increase the N-use efficiency and to decrease N losses. It involves implementing an iterative set (cycle) of common management activities, carried out annually:

(a) Analysis of:
    (i) The N demands of crops and animals;
    (ii) The available N sources;
    (iii) The storage conditions and possible leakages;
    (iv) The available techniques, methods and procedures for using N efficiently;
(b) Decision-making, including:
    (i) Development of options on the basis of the previous analyses;
    (ii) Assessment of the consequences of the various options;
    (iii) Selecting the best option for achieving both agronomic and environmental targets;
(c) Planning, including:
    (i) Working out in broad outline the things that need to be done and measured: when and where and how and with how much;
    (ii) Making the actual plan, that allocates the available nutrients in a way that maximizes the economic benefit, while minimizing the environmental impact and satisfying environmental limits;
(d) Execution, i.e.:
    (i) Implementation of the N-management plan in practice;
    (ii) Taking into account actual environmental conditions;
    (iii) Taking into account best management guidelines and recommendations;

(e) Monitoring and control, i.e.:

    (i) Collecting data on yield and N contents;

    (ii) Making N input-output balances;

(f) Evaluation (verification and control of achievements relative to the set objectives) including:

    (i) Nitrogen surplus of the input-output balance sheet (Nsurplus);

    (ii) N use efficiency (NUE).

39. The N input-output balance (also referred to as the farm-gate balance) can be seen as the monitoring tool to help achieve improvement in N management (e.g., Jarvis and others, 2011). It records at the farm level all N inputs and all N outputs in useful products. The difference between total N inputs and total N outputs is the Nsurplus, while the ratio between total N output in useful products and total N input is a measure of the NUE. The Nsurplus is an indicator for the pressure on the environment, and is expressed in terms of N per ha per year. NUE is an indicator for the efficiency of resources use (how much protein-N in food is produced per unit of input N) and is expressed in terms of kg per kg (Doberman, 2007). Both, Nsurplus and NUE depend highly on farming systems and management level. Indicative target values can be set for both Nsurplus and NUE, depending again on the farming system and management level. In some countries, information about the farm N balance, Nsurplus and NUE may be seen as confidential information.

40. Nitrogen input-output balances have been used in research for more than 100 years, on farms in some countries for more than 10 years now and also as a regulatory tool. However, there is less experience with the use of input-output N balances as a tool to decrease NH_3 emissions specifically. The effectiveness of N input-output balances to decrease NH_3 emissions is greatest on farms with high livestock density. Constructing N input-output balances at the farm level requires knowledge about bookkeeping in general and about N inputs and outputs. The experience so far is that these balances are easily understood by farmers and therefore can be used easily in communications and for comparing different farms and their performances. This is especially the case because an improvement in the N balance provides the basis for farmers to reduce costs in the purchase of mineral fertilizers. Similarly, for “organic” farmers, where mineral fertilizers are not used, improving the N balance makes better use of N as a scarce resource on the farm.

41. Nsurplus and NUE depend on the farming system and on the agronomic and environmental objectives. Hence, target levels for Nsurplus and NUE are farm-type specific, and must be considered and evaluated from a regional perspective.

42. The progress in N management can be evaluated on the basis of changes in Nsurplus and NUE over time, for a specific farm or group of farms. A five-year period should be considered to account for inter-annual variations in weather conditions or incidental losses. Improvement in N management will be reflected in decreases in Nsurplus and increases in NUE. The improvement in N management can continue until a level of “best management practice” has been achieved. This “best management level” is commonly set by experimental farms or by the upper 5 percentile of practical farms. Hence, the improvement in N management performance can continue until the farms achieve the level that has been achieved by the upper 5 percentile of practical farms. Farms in Denmark and the Netherlands have been able to achieve decreases in Nsurplus and increases in NUE on the order of 30% in 5-year periods and 50% in 10-year periods (e.g., Mikkelsen and others, 2010; J. Oenema and others, 2011). Further decreases in Nsurplus and further increases in NUE slow down greatly once a level of best management practice has been achieved.

43. Indicative target levels for Nsurplus and NUE are presented in table 2. Note that NUE is related inversely and non-linearly to Nsurplus.

44. The indicative costs of making an N input-output balance are in the range of €200–€500 per farm per year, depending on the farming system and on the assistance of accountancy and/or advisory services. Note that costs associated with education, promotion and start-up are not considered here. In some countries, data availability may be a constraint for farms in practice, but likely not for “model farms” and “pilot farms”. The costs tend to decrease over time (learning effect).

45. The net cost of improving N management and thereby increasing NUE and decreasing Nsurplus are in the range of -€1–€1 per kg N (Reis, forthcoming). The net costs are the result of gains through fertilizer savings and increased production performance, and gross cost related to sampling and analyses, training and advisory costs.

46. National N budgets for agriculture provide insight into: (a) the N cost of food production; (b) N losses associated with food production at the national level; and (c) possible options for improving NUE at the national level. National N budgets, when expressed in terms of kilogram per hectare per year also provide a means of comparing the agricultural sectors of different ECE countries and assessing progress towards reduced overall losses from national N cycles. Uniform formats and procedures (online) have been established for constructing such national N budgets. The costs of establishing an N budget at the national level are in the range of €10,000–€100,000 per year, depending on the availability of data statistics. Note that costs associated with education, promotion and start-up are not considered here. In some countries, data availability may be a constraint. A separate guidance document detailing the methods for calculating national N budgets has been prepared by the Task Force on Reactive Nitrogen and adopted by the Executive Body (ECE/EB.AIR/119).[10]

Table 2

Indicative ranges for target Nsurplus and NUE as a function of farming system, crop species and animal categories

Farming systems	*Species/categories*	*NUE (kg N/kg N)*	*N surplus, (kg/ha/yr)*	*Comments*
Specialized cropping systems	Arable crops	0.6–0.9	0–50	Cereals have high NUE. Root crops have low NUE.
	Vegetables	0.4–0.8	50–100	Leafy vegetables have low NUE.
	Fruits	0.6–0.9	0–50	
Grassland-based	Dairy cattle	0.3–0.5	100–150	High milk yield, high NUE. Low stocking density, low Nsurplus. Presence of legumes improves NUE.
Ruminant systems	Beef cattle	0.2–0.4	50–150	Veal production, high NUE. Two-year-old beef cattle, low NUE.
	Sheep and goats	0.2–0.3	50–150	
Mixed crop-animal systems	Dairy cattle	0.4–0.6	50–150	High milk yield, high NUE. Concentrate feeding, high NUE.
	Beef cattle	0.3–0.5	50–150	
	Pigs	0.3–0.6	50–150	
	Poultry	0.3–0.6	50–150	
	Other animals	0.3–0.6	50–150	
Landless systems	Dairy cattle	0.8–0.9	n.a.[a]	N Output via milk, animals and manure ~equals N input. Nsurplus is gaseous N losses from housing and storages.
	Beef cattle	0.8–0.9	n.a.[a]	
	Pigs	0.7–0.9	n.a.[a]	
	Poultry	0.6–0.9	n.a.[a]	
	Other animals	0.7–0.9	n.a [a]	

[a] Not applicable, as these farms have essentially no land. However, the N surplus can be expressed in kg per farm per year. In the case that all animal products, including animal manure and all residues and wastes, are exported, the target N surplus can be between 0 kg and 1,000 kg per farm per year, depending on farm size and gaseous N losses.

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[10] Guidance document on national nitrogen budgets (ECE/EB.AIR/119); available from http://www.unece.org/environmental-policy/treaties/air-pollution/guidance-documents-and-other-methodological-materials/gothenburg-protocol.html

Chapter

4

Livestock feeding strategies

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47. Gaseous N losses from livestock production originate from the faeces (dung) and urine excreted by the livestock. The animal feed composition and the feed management has a strong influence on animal performance and on the composition of the dung and urine, and thereby also on the emissions of NH_3. This section focuses on feeding strategies to reduce NH_3 emissions. Supplementary information about "feeding strategies" is provided in annex II.

48. *Reference techniques*: The abatement strategies described in this chapter are not defined and assessed against a uniform reference (or unabated or baseline) feeding strategy, because these reference feeding strategies are different for different ECE countries. A distinction also has to be made between different animal categories, as animal feed requirements and the resulting N excretion greatly differ between animal categories.

49. Low-protein animal feeding is one of the most cost-effective and strategic ways of reducing NH_3 emissions. For each per cent (absolute value) decrease in protein content of the animal feed, NH_3 emissions from animal housing, manure storage and the application of animal manure to land are decreased by 5%–15%, depending also on the pH of the urine and dung. Low-protein animal feeding also decreases N_2O emissions, and increases the efficiency of N use in animal production. Moreover, there are no animal health and animal welfare implications as long as the requirements for all amino acids are met.

50. Low-protein animal feeding is most applicable to housed animals and less for grassland-based systems with grazing animals, because grass is in an early physiological growth stage and thus high in degradable protein, and grassland with leguminous species (e.g., clover and lucerne) have a relatively high protein content. While there are strategies to lower the protein content in herbage (balanced N fertilization, grazing/harvesting the grassland at later physiological growth stage, etc.), as well as in the ration of grassland-based systems (supplemental feeding with low-protein feeds), these strategies are not always fully applicable.

51. The economic cost of animal feeding strategies to lower the NH_3 volatilization potential of the animal excrements through adjusting the crude protein (CP) content depends on the initial animal feed composition and on the prices of the feed ingredients on the market. In general, the economic costs range from -€2 to +€2 per kilogram NH_3-N saved, i.e., there are potential net gains and potential net costs. Commonly, the economic costs increase when the target for lowering the NH_3 volatilization potential increases. The increasing marginal costs relate in part to the cost of synthetic amino acids supplementation relative to using soybeans. The costs of amino acids supplementation tend to go down. The cost of supplementation of amino acids increases when the target protein content in the animal feed is lowered (see also annexes I and II).

Category 1 feeding strategies for dairy and beef cattle

52. Lowering CP of ruminant diets is an effective and category 1 strategy for decreasing NH_3 loss. The following guidelines hold (table 3):

(a) The average CP content of diets for dairy cattle should not exceed 15%–16% in the dry matter (DM) (Broderick, 2003; Swensson, 2003). For beef cattle older than 6 months this could be further reduced to 12%;

(b) Phase feeding can be applied in such a way that the CP content of dairy diets is gradually decreased from 16% of DM just before parturition and in early lactation to below 14% in late lactation and the main part of the dry period;

(c) Phase feeding can also be applied in beef cattle in such a way that the CP content of the diets is gradually decreased from 16% to 12% over time.

Table 3
Indicative target levels for CP content (% of the dry mass of the ration), and resulting NUE of cattle product in mass fractions (kg/kg)

Cattle species	*CP (%)*[a]	*NUE of cattle product (kg/kg)*
Milk + maintenance, early lactation	15–16	0.30
Milk + maintenance, late lactation	12–14	0.25
Non-lactating (dry) dairy cows	13–15	0.10
Veal	17–19	0.45
Cattle < 3 months	15–16	0.30
Cattle 3–18 months	13–15	0.15
Cattle > 18 months	12	0.05

[a] The values presented here can be considered as “high ambition level”.

53. In many parts of the world, cattle production is grassland-based or partly grassland-based. In such systems, protein-rich grass and grass products form a significant proportion of the diet, and the target values for CP noted in table 3 may be difficult to achieve, given the high CP content of grass from managed grasslands. The CP content of fresh grass in the grazing stage (2,000–2,500 kg DM/ha) is often in the range of 18%–20% (or even higher, especially when legumes are present), the CP content of grass silage is often between 16% and 18% and the CP content of hay is between 12% and 15% (e.g., Whitehead, 2000). In contrast, the CP content of maize silage is only in the range of 7%–8%. Hence, grass-based diets often contain a surplus of protein and the magnitude of the resulting high N excretion strongly depends on the proportions of grass, grass silage and hay in the ration and the protein content of these feeds. The protein surplus and the resulting N excretion and NH_3 losses will be highest for grass (or grass-legume)-only summer rations with grazing of young, intensively fertilized grass or grass legume mixtures. However, urine excreted by grazing animals typically infiltrates into the soil before substantial NH_3 emissions can occur and overall NH_3 emissions per animal are therefore less for grazing animals than for those housed where the excreta is collected, stored and applied to land.

54. The NH_3 emission reduction achieved by increasing the proportion of the year the cattle spent grazing outdoors will depend on the baseline (emission of ungrazed animals), the time the animals are grazed, and the N fertilizer level of the pasture. The potential to increase grazing is often limited by soil type, topography, farm size and structure (distances), climatic conditions, etc. It should be noted that grazing of animals may increase other forms of N emissions (e.g., nitrate-N leaching and N_2O emissions). However, given the clear and well quantified effect on NH_3 emissions, increasing the period that animals are **grazing all day can be considered as a category 1 strategy** to reduce emissions, but depending on grazing time (see also paras. 52, 184 and 185). The actual abatement potential will depend on the base situation of each animal sector in each country. The effect of changing the period of partial housing (e.g., grazed during daytime only) is less certain and is rated as a category 2 strategy. Changing from a fully housed period to grazing for part of the day is less effective in reducing NH_3 emissions than switching to complete (24-hour) grazing, since buildings and stores remain dirty and continue to emit NH_3. Grazing management (strip grazing, rotational grazing, continuous grazing) is expected to have little additional effect on NH_3 losses and is considered a category 3 strategy.

55. In general, increasing the energy/protein ratio in the diet by using “older” grass (higher sward surface height) or swathed forage cereal and/or supplementing grass by high energy feeds (e.g., silage maize)

is a category 1 strategy. However, for grassland-based ruminant production systems, the feasibility of these strategies may be limited, as older grass may reduce feeding quality, especially when conditions for growing high energy feeds are poor (e.g., warm climates), and therefore have to be purchased. Hence, full use of the grass production would no longer be guaranteed (under conditions of limited production, e.g., milk quotas or restrictions to the animal density). Hence, improving the energy/protein equilibrium on grassland-based farms with no possibilities of growing high energy feeds is therefore considered a category 2 strategy.

Category 1 feeding strategies for pigs

56. Feeding measures in pig production include phase feeding, formulating diets based on digestible/available nutrients, using low-protein amino acid-supplemented diets, and feed additives/supplements. These are all considered category 1 techniques. Further techniques are currently being investigated (e.g., different feeds for males (boars and castrated males) and females) and might be additionally available in the future.

57. The CP content of the pig ration can be reduced if the amino acid supply is optimized through the addition of synthetic amino acids (e.g., lysine, methionine, threonine, tryptophan) or special feed components, using the best available information on “ideal protein” combined with dietary supplementation.

58. A CP reduction of 2%–3% in the feed can be achieved, depending on pig production category and the current starting point. The resulting range of dietary CP contents is reported in table 4. The values in the table are indicative target levels and may need to be adapted to local conditions. It has been shown that a decrease of 1% CP in the diet of finishing pigs results in a 10% lower total ammoniacal nitrogen (TAN) content of the pig slurry and 10% lower NH_3 emissions (Canh and others, 1998b).

Table 4

Indicative target CP levels in feed for pig rations

Species	*Phases*	*CP content (%)*[a]
Weaner	< 10 kg	19–21
Piglet	< 25 kg	17–19
Fattening pig	25–50 kg	15–17
	50–110 kg	14–15
	> 110 kg	12–13
Sows	Gestation	13–15
	Lactation	15–17

Source: Based on European Commission, 2003.

[a] With adequately balanced and optimal amino acid supply. The values presented here can be considered as “medium to high ambition level” (see annex II for a further specification of target CP levels).

Category 1 feeding strategies for poultry

59. For poultry, the potential for reducing N excretion through feeding measures is more limited than for pigs because the conversion efficiency currently achieved on average is already high and the variability within a flock of birds is greater. A CP reduction of 1%–2% may be achieved depending on the species and the current starting point. The resulting range of dietary CP contents is reported in table 5. The values in the table are indicative target levels, which may need to be adapted to local conditions. Further applied nutrition research is currently being carried out in EU member States and North America and this may support further possible reductions in the future. A reduction of the CP content by 1%–2% is a category 1 measure for growers and finishers.

Table 5

Indicative target CP levels in feed for poultry

Species	*Phases*	*CP content (%)*[a]
Chicken, broilers	Starter	20–22
	Grower	19–21
	Finisher	18–20
Chicken, layers	18–40 weeks	15.5–6.5
	40+ weeks	14.5–15.5
Turkeys	< 4 weeks	24–27
	5–8 weeks	22–24
	9–12 weeks	19–21
	13+ weeks	16–19
	16+ weeks	14–17

Source: Based on European Commission, 2003.

[a] With adequately balanced and optimal amino acid supply. The values presented here can be considered as "medium to high ambition level" (see annex II for a further specification of target CP levels).

Chapter
5

Livestock housing

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A. Housing systems for dairy and beef cattle

60. Techniques to reduce NH_3 emissions in cattle housing apply one or more of the following principles:

(a) Decreasing the surface area fouled by manure;

(b) Absorption or adsorption by bedding (e.g., straw);

(c) Rapid removal of urine; rapid separation of faeces and urine;

(d) Decreasing the velocity and temperature of air above the manure, except where manure is being dried;

(e) Reducing the temperature of the manure;

(f) Decreasing soiled areas in houses and hard standings by increased grazing;

(g) Air scrubbing, i.e., removing NH_3 from the air through forced ventilation in combination with air scrubbers.

61. When using measures to abate emission from cattle houses, it is important to minimize loss of the conserved NH_3 during downstream handling of the manure, in storage and spreading to maximize the benefit from the cost of abatement.

62. Housing systems for cattle vary across the ECE region. While loose housing is most common, dairy cattle are still kept in tied stalls in some countries. In loose housing systems all or part of the excreta is collected in the form of slurry. In systems where solid manure is produced (such as straw-based systems), it may be removed from the house daily or it remain there for up to the whole season, such as in deep litter stables. The system most commonly researched is the “cubicle house” for dairy cows, where NH_3 emissions arise from fouled slatted and/or solid floors and from manure in pits and channels beneath the slats/floor.

63. *Reference system:* For cattle housing, the cubicle house is taken as the reference system (table 6). Cattle held in tied stalls emit less NH_3 than in loose housing systems, because a smaller floor area is fouled with dung and urine. However, tied systems are not recommended in consideration of animal welfare unless daily exercise periods are applied. The tied housing system is the traditional reference system for maintaining continuity in emission inventories.

64. *Animal welfare considerations* tend to lead to an increase of soiled walking area per animal, increased ventilation, possibly cooler winter temperatures and an overall increase in emissions. Changes in building design to meet the new animal welfare regulations in some countries (e.g., changing from tied stall to cubicle housing) will therefore increase NH_3 emissions unless abatement measures are introduced at the same time to combat this increase. Changes in building or new construction to meet animal welfare

requirements present an important opportunity to introduce NH_3 mitigation measures at the same time, thereby reducing the costs of the mitigation measures relative to retrofits.

65. *Solid versus slurry manure systems.* Straw-based systems producing solid manure for cattle are not likely to emit less NH_3 in the animal houses than slurry-based systems. Further, N_2O and di-nitrogen (N_2) losses due to (de)nitrification tend to be larger in litter-based systems than slurry-based systems. While straw-based solid manure can emit less NH_3 than slurry after surface spreading on fields (e.g., Powell and others, 2008), slurry provides a greater opportunity for reduced emissions applications. The physical separation of faeces (which contains urease) and urine in the housing system reduces hydrolysis of urea, resulting in reduced emissions from both housing and manure spreading (Burton, 2007; Fangueiro and others, 2008a, 2008b; Møller and others, 2007). Verification of any NH_3 emission reductions from using solid-manure versus slurry-based systems and from solid-liquid separation should consider all the stages of emission (housing, storage and land application).

Category 1 techniques

66. *The "grooved floor" system* for dairy and beef cattle housing, employing "toothed" scrapers running over a grooved floor, is a reliable technique to abate NH_3 emissions. Grooves should be equipped with perforations to allow drainage of urine. This results in a clean, low-emission floor surface with good traction for cattle to prevent slipping. Ammonia emission reduction ranges from 25% to 46% relative to the reference system (Smits, 1998; Swierstra, Bram and Smits, 2001).

67. In houses with traditional slats (either non-sloping, 1% sloping or grooved), optimal barn climatization with roof insulation (RI) and/or automatically controlled natural ventilation (ACNV) can achieve a moderate emission reduction (20%) due to the decreased temperature (especially in summer) and reduced air velocities (Braam, Ketelaars and Smits 1997; Bram and others, 1997; Smits, 1998; Monteny, 2000).

68. Decreasing the amount of animal excrement in animal housing systems through increased grazing is an effective measure to decrease NH_3 emissions. Though emissions from grazing will increase when animals are kept outside, NH_3 emissions from animal housing systems will decrease much more, provided surfaces in the house are clean while the animals are grazing outside. Total annual emissions (from housing, storage and spreading) from dairy systems may decrease by up to 50% with nearly all-day grazing (Bracher and others, forthcoming), as compared with animals that are fully confined. While increased grazing is a reliable emission reduction measure for dairy cows, the amount of emission reduction depends on the daily grazing time and the cleanliness of the house and holding area. Grazing is category 1 if the animals are grazed all day or if very little floor area is contaminated with manure each day. Less than 18 grazing hours per day must be considered as category 2 because of the uncertainty in quantifying emissions. In some cases grazing can contribute to increased leaching or increased pathogen and nutrient loading of surface water (see also paras. 40, 184 and 185).

Category 2 techniques

69. *Different improved floor types* based on slats or solid, profiled concrete elements have been tested in the Netherlands. These designs combine emission reduction from the floor (increased run-off of urine) and from the pit (reduction of air exchange by rubber flaps in the floor slots). The emission abatement efficiency depends on the specific technical characteristics of the system. The measure is therefore considered as category 2 and is not included in table 6.

70. *Bedding material* in animal housing can affect NH_3 emission. The physical characteristics (urine absorbance capacity, bulk density) of bedding materials are of more importance than their chemical characteristics (pH, cation exchange capacity, carbon to nitrogen ratio) in determining NH_3 emissions from dairy barn floors (Misselbrook and Powell, 2005; Powell, Misselbrook and Casler, 2008; Gillespy and others, 2009). However, further assessment is needed on the effect of bedding on emissions for specific systems while taking into account the whole manure management path.

71. *Chemical or acid air scrubbers,* while effective in decreasing NH_3 emissions from force-ventilated pig housing, cannot generally be implemented in cattle housing which are mostly naturally ventilated across the ECE region. Also, there are few data for scrubbers on cattle housing so they are currently considered a category 2 technique (Ellen and others, 2008).

Category 3 techniques

72. *Scraping and flushing systems*. A number of systems have been tried involving the regular removal of the slurry from the floor to a covered store outside of the building. These involve flushing with water, acid, diluted or mechanically separated slurry, or scraping with or without water sprinklers. In general, these systems have proven to be ineffective or too difficult to maintain. The use of smooth and/or sloping floors to assist in scraping or flushing contributes to slipping which is very detrimental to cow health. These systems are therefore considered as category 3 techniques.

Table 6

Ammonia emissions of different cattle housing systems (reference systems and category 1 and 2 techniques)

Housing type	*Reduction (%)*	*NH_3 emission*[a] *(kg/cow place/year)*
Cubicle house (reference system)	n.a.	12.0[b]
Tied system[c] (traditional reference system)	n.a.	4.8
Grooved floor (cat. 1)	25–46	9.0
Optimal barn climatization with roof insulation (cat. 1)	20	9.6
Chemical air scrubbers (forced ventilation systems only) (cat. 2)	70–90	1.2
Grazing 12h/24h (cat. 2), relative to ref. 1	10	10.8[d]
Grazing 18h/24h (cat. 1) relative to ref. 1	30	8.4[d]
Grazing 22h/24h (cat. 1) relative to ref. 1	50	6.0[d]

Abbreviation: n.a. = not applicable.

[a] Emissions with full-time housing of the animals.

[b] Based on a walking area of 4–4.5 m^2 per cow and permanent housing.

[c] Tied systems are not favoured for animal welfare reasons. These systems are traditional reference systems for continuity in emission inventories.

[d] These numbers hold for season-long grazing (assumed about 200 days). They show the relative reduction of annual emissions as compared with the reference system with no grazing. Grazing for part of the days requires that barn surfaces are always kept clean.

B. Housing systems for pigs

73. *Reference system:* Emissions from fully slatted pig houses with a storage pit underneath are taken as the reference, although in some countries these systems are prohibited for animal welfare reasons.

74. Designs to reduce NH_3 emissions from pig housing systems have been described in detail in European Commission (2003), and apply the following principles:

(a) Reducing manure surfaces such as soiled floors, slurry surfaces in channels with sloped walls. Partly slatted floors (~50% area), generally emit less NH_3, particularly if the slats are metal- or plastic-coated rather than concrete, allowing the manure to fall rapidly and completely into the pit below. Emissions from the non-slatted areas are reduced by inclined, smooth surfaces, by locating the feeding and watering facilities to minimize fouling these areas, and by good climate control in the building;

(b) Removing the slurry from the pit frequently to an external slurry store with vacuum or gravity removal systems or by flushing systems at least twice a week;

(c) Additional treatment, such as liquid/solid separation;

(d) Circulating groundwater in floating heat exchangers to cool the surface of the manure in the under-floor pit to at least 12°C. Constraints include costs and need to locate a source of groundwater away from the source of drinking water;

(e) Changing the chemical/physical properties of the manure such as decreasing pH;

(f) Using surfaces which are smooth and easy to clean (see subpara. (a) above);

(g) Treatment of exhaust air by acid scrubbers or biotrickling filters;

(h) Lowering the indoor temperature and ventilation rate, taking into account animal welfare and production considerations, especially in winter;

(i) Reducing air flow over the manure surface.

75. For a given slat width, manure drains from concrete slats less efficiently than from steel- and plastic-covered slats and this is associated with greater emissions of NH_3. Note that steel slats are not allowed in some countries for animal welfare reasons.

76. These cross-media effects have been taken into account in defining BAT for the various housing designs. For example, frequent flushing of slurry (normally once in the morning and once in the evening) causes nuisance odour events. Flushing slurry also consumes energy unless manually operated passive systems are used.

77. Use of straw in pig housing is expected to increase due to concern for the welfare of the pigs. In conjunction with (automatically controlled) naturally ventilated housing systems, straw allows the animals to self-regulate their temperature with less ventilation and heating, reducing energy consumption. In systems with litter, the pen is sometimes divided into solid areas with litter and slatted dunging areas. However, pigs do not always use these areas in the desired way, using the littered area to dung and the slatted area to cool off in warm weather. Generally, pens should be designed to accommodate desired excreting behaviour of pigs to minimize fouling of solid floors. This is more difficult in regions with a warm climate. Note that integrated evaluation of straw use should consider the added cost of the straw and mucking out the pens; possible increased emissions from storage and application of manure with straw; and the benefit of adding organic matter to the soil.

78. *Reference technique for growers/finishers:* The reference system, used commonly in Europe, is a fully slatted floor with a deep manure pit underneath and mechanical ventilation; emission ranges from 2.4 to 3.2 kg NH_3 per pig place per year. Since growers/finishers are always housed in a group, most systems used for group housing of sows are applicable to growers.

79. *Reference technique for farrowing sows:* Farrowing sows in Europe are generally housed in crates with steel or plastic slatted floors and a deep manure pit underneath. In the majority of houses, sows are confined while piglets are free to walk around. All houses have controlled ventilation and often a heated area for the piglets during their first few days after birth. The difference between fully and partly slatted floors is not as distinct for farrowing sows as for growers because the sow is confined and excretion generally takes place in the slatted area. Reduction techniques therefore focus on alterations in the manure pit.

80. *Reference technique for mating and gestating sows*: The reference system for housing of mating and gestating sows is the fully slatted floor (concrete slats) with a deep pit. Mating and gestating sows are currently housed individually or in groups. Throughout the EU, group housing is compulsory for newly built sow housing and starting in 2013 group housing will be required also for all mating and gestating sows for a four-week period after insemination. Group-housing systems require special feeding systems (e.g., electronic sow feeders or open stalls) and a pen design that influences sows to use distinct areas for manuring and lying. Group housing has similar emission levels to individual housing (Groenestein and others, 2001) and similar emission reduction techniques can be employed.

81. *Reference technique for weaners*: Weaners are group housed either in conventional pens or flat decks (raised pens). Because the manure removal method is similar, it is assumed that reduction measures applicable to conventional weaner pens can also be applied to flat decks.

82. Table 7 summarizes the design and techniques for reducing emissions, including estimated efficiencies and costs, for all classes of pig houses. The estimated costs vary widely due to farm-specific conditions such as building size. Note that some techniques are very costly to apply in existing houses. Information about the economic costs of low-emission techniques and strategies can be found in Reis (forthcoming).

83. A study conducted in 2007 showed that the overall cost of NH_3 emission reduction from pig housing systems in the Netherlands, using mainly air scrubbers, averaged €0.016 per kg of pig carcass produced

(Baltussen and others, 2010). At the time of the study, only large (IPPC) farms already had technologies installed to reduce emissions by a target of 40%–60% (from combined housing and storage). However, it is estimated that cost will rise to €0.04 per kg of pig carcass in 2013 when even small pig farms in the Netherlands will have to comply with both emission and welfare standards. Assuming 200 kg of pig meat is produced per pig place per year, the cost of the NH_3 emission reduction and welfare measures are €7.2 per pig place or €3 per kg NH_3-N saved; both of these estimates are considered robust in the Netherlands. The estimates do not take into account that some of the conserved NH_3 may be lost further down the manure chain.

84. The various systems for reducing emissions reported in paragraphs 80–90 are all based on the principles noted in paragraph 69.

Category 1 techniques

85. Ammonia emission can be reduced by 25% by reduction of emitting surface area through frequent and complete vacuum-assisted drainage of slurry from the floor of the pit. Where this is possible to do, this technique has no cost.

86. Partly slatted floors covering 50% of floor area generally emit 15%–20% less NH_3, particularly if the slats are metal or plastic-coated which is less sticky for manure than concrete. Decreasing risk of emissions from the solid part of the floor can be achieved by using an inclined (or convex), smoothly finished surface; by appropriate siting of the feeding and watering facilities to minimize fouling of the solid areas; and by good climate control (Aarnink and others, 1996; Guigand and Courboulay, 2007; Ye and others, 2008a, 2008b).

87. Further reduction of the emitting area can be achieved by making both the partly slatted area and the pit underneath smaller. With the smaller slatted area, the risk of greater fouling of the solid area can be mitigated by installing a small second slatted area with a water canal underneath at the other side of the pen where the pigs tend to eat and drink. The canal is filled with about two centimetres (cm) of water to dilute any manure that might eventually drop into it. This slatted area will have low emissions because any manure dropped here will be diluted. This combined manure-canal and water-canal system can reduce NH_3 emissions by 40%–50% depending on the size of the water canal.

88. Reducing the emitting surface area by having one or two slanted pit walls, in combination with partly slatted floors and frequent manure removal, can reduce emissions by up to 65%.

89. Reducing the emitting surface area with shallow V-shaped gutters (maximum 60 cm wide, 20 cm deep) can reduce emission in pig houses by 40% to 65%, depending on pig category and the presence of partly slatted floors. The gutters should be flushed twice a day with the liquid (thin) fraction of the slurry rather than water; flushing with water dilutes the manure and increases the cost of transporting it.

90. For lactating sows, emission reduction of 65% can be achieved by reducing the emitting area by means of constructing a pan under the slatted floor of the pen. The pan is a sloped subfloor (at least 3°) with manure drainage at the lowest point. Although the pan can be retrofitted into existing housing, in practice it may be quite costly to alter the manure drainage system.

91. Reducing NH_3 emissions can also be achieved by acidifying the slurry to shift the chemical balance from NH_3 to NH_4^+. The manure (especially the liquid fraction) is collected into a tank with acidified liquid (usually sulphuric acid, but organic acids can be used as well) maintaining a pH of less than 6. In piglet housing emission reduction of 60% has been observed.

92. Surface cooling of manure with fins using a closed heat exchange system is a category 1 technique with a reduction efficiency of 45%–75% depending on animal category and surface of cooling fins. This technique is most economical if the collected heat can be exchanged to warm other facilities such as weaner houses (Huynh and others, 2004). In slurry systems this technique can be retrofitted into existing buildings. This system is not applicable when straw bedding is used or when the feed contains a lot of roughage because a layer of floating residue may develop on top of the slurry.

93. Treatment of exhaust air by acid scrubbers (mainly sulphuric acid) or biotrickling filters has proven to be practical and effective for large-scale operations in Denmark, Germany, France and the Netherlands and hence is category 1 (e.g., Melse and Ogink, 2005; Guingand, 2009). This is most economical when installed in new houses because retrofitting in existing housing requires costly modification of ventilation systems.

Acid scrubbers have demonstrated NH_3 removal efficiencies of 70%–90%, depending on their pH-set values. Scrubbers and biotrickling filters also reduce odour and particulate matter by 75% and 70%, respectively (Guingand, 2009). Further information is needed on the suitability of these systems in South and Central Europe. Operational costs of both acid scrubbers and trickling filters are especially dependent on the extra energy use for water recirculation and to overcome increased back pressure on the fans. Optimization methods are available to minimize costs (Melse, Hofschereuder and Ogink, 2012) and costs will be lower for large operations.

Category 2 techniques

94. Floating balls in manure pits may reduce emissions by 25% by partially covering the emitting surface. Manure dropping on the balls causes them to turn, and because of their non-stick surface, the clean side of the ball rotates upward. This technique can be used in existing houses. Because this technique has not been evaluated outside the Netherlands, it is considered category 2.

95. A V-shaped belt installed underneath the slatted floor can be used to remove manure frequently from the house. The shape of the belt allows the urine to continuously run off, segregating it from the urease enzyme contained in the faeces, thus minimizing the conversion (hydrolysis) of urea to NH_3. Due to both rapid removal and reduced NH_3 production, NH_3 emission is reduced by about 70% (Aarnink and others, 2007). Note that with this technique no pit is required, thus offsetting some of the building construction costs. Also, by separating the manure, efficient application of P and N to the soil can be arranged. The V-belt system is considered a category 2 technique because it has only been evaluated in the Netherlands. It has potential for all pig categories but has been evaluated only with fatteners.

Table 7

Category 1 and 2 techniques: reduction and costs of low-emission housing systems for pigs

Category 1 technique (unless specified cat. 2)	*NH_3 emission (kg NH_3/ place/year)*	*Emission reduction (%)*	*Extra cost (€/place/ year)*[a]	*Extra cost (€/kg NH_3-N reduced)*
Gestating sows	**4.20**			
Frequent manure removal with vacuum system		25	0[b]	0[b]
Flushing gutters		40	33	23
Cooling manure surface		45	19	12
(Group) housing with feeding stalls and manure pit with slanted walls		45	16	10
Floating balls on manure surface (cat. 2)		25	14	16
Air scrubbing techniques		70–90	22–30	8–10
Lactating Sows	**8.30**			
Water and manure channel		50	2	0.5
Manure pan underneath		65	40–45	9
Cooling manure surface		45	45	15
Floating balls on manure surface (cat. 2)		25	14	8
Air scrubbing techniques		70–90	35–50	7–10
Piglets after weaning	**0.65**			
Partially slatted floor with reduced pit		25–35	0	0
Frequent manure removal with vacuum system		25	0[b]	0[b]
Partly slatted floors and flushing gutters		65	5	14
Partly slatted floor and collection in acidified liquid		60	5	15
Partly slatted floor and cooling manure surface		75	3–4	7–10
Partly slatted floor and manure channel with slanted walls		65	2	5–6
Floating balls on manure surface (cat. 2)		25	1	6–7
Air scrubbing techniques		70–90	4–5	8–12
Growers-finishers	**3.0**			
Partially slatted floor with reduced pit		15–20	0	0
Frequent manure removal with vacuum system		25	0[b]	0[b]
Partially slatted floor with water and manure channel		40	2	2
Partially slatted floor with water channel and manure channel with slanted walls		60–65	3–5	2–3
Flushing gutters		40	10–15	10–15
Partially slatted floor and cooling manure surface		45	5–7	4–6
Floating balls on manure surface (cat. 2)		25	2	4
Partially slatted floors and separated removal of liquid and solid manure fraction by V-shaped belt (cat. 2)		70	0–5	0–3
Air scrubbing techniques		70–90	10–15	5–9

Note: For economic cost of the abatement techniques, see Reis (forthcoming).

[a] Prices are calculated based on new buildings. Only cooling systems, floating balls and scrubbers can be installed in existing buildings, see text for explanation about retrofitting.

[b] If vacuum manure removal system is already installed.

C. Housing systems for poultry

96. Designs to reduce NH_3 emissions from poultry housing systems apply the following principles:

(a) Reducing emitting manure surfaces;

(b) Removing the manure frequently to an external slurry store (e.g., with belt removal systems);

(c) Quickly drying the manure;

(d) Using surfaces which are smooth and easy to clean;

(e) Treatment of exhaust air by acid scrubbers or biotrickling filters;

(f) Lowering the indoor temperature and ventilation as animal welfare and/or production allow.

1. Housing systems for laying hens

97. The evaluation of housing systems for layers in the EU member States has to consider the requirements laid down by Council Directive 1999/74/EC of 19 July 1999 laying down minimum standards for the protection of laying hens. This Directive prohibits the use of conventional cage systems starting in 2012. Instead, only enriched cages (also called furniture cages), or non-cage systems, such as litter (or deep litter) housing systems or aviary systems, are allowed.

98. *Reference system for conventional cage housing*. This system uses an open manure storage underneath the cages. Although banned in the EU from 2012, some ECE States still house laying hens in conventional cages and most of the reports on NH_3 emission reduction refers to this type of housing as a reference. This reference is also maintained for continuity in emission inventory calculation.

99. *Reference system for "enriched" cage houses*. This system can replace conventional cages without the need for significant alteration of existing building. Enriched cages provide the laying hens increased space including areas for nesting, scratching and perching. Birds are kept in groups of 40–60. A (ventilated) belt placed under cages is the most common method of manure removal. The enriched cage housing measures are presented in a separate table because the reference system, rather than conventional cages, is an enriched cage with a belt underneath to remove manure regularly without drying. For animal welfare reasons enriched cages are not allowed in the Netherlands and in Germany, instead they have colony housing or *Kleingruppenhaltung*. The difference with enriched cages is a larger surface area per animal, higher cages and more defined areas with litter and nests. Ellen and Ogink (2009) substantiated that the same NH_3 emission factors can be applied as for enriched cages.

100. *Reference system for non-caged houses: deep-pit housing in combination with partly littered floor.* In this system, the building is characteristically equipped with 80- to 90-cm high dropping pits covered with wooden or plastic slats or wire mesh. The manure is collected in pits under the slats, which occupy two thirds of the floor area. The remaining one third of the floor is covered with litter such as sand, wood shavings or straw and used for scratching and dust-bathing. The stocking density in these houses is up to nine hens per m² of floor area.

101. *Aviary system (perchery).* The building is divided into different functional areas used for feeding and drinking, egg laying, scratching and resting, with litter is provided. The available surface area is increased by means of elevated slatted floors combined with stacks allowing a stocking density of up to 18 hens per m² of floor area. As in cage systems, aviaries employ belts placed under the tiers to collect the manure; ventilated belts can be installed for collection, drying and removal of litter.

102. In some countries, the definition of "free range" includes deep-pit housing systems with partly littered floor (or deep litter) or aviary systems providing outdoor access for the birds. In countries where "free-range " hens are housed on solid or partly slatted floors, the solid floor area is covered with litter and the hens have some access to the outdoors. Manure accumulates either on the solid floor or under the slatted area for the 14-month laying period.

Category 1 techniques

103. Ammonia emissions from battery deep-pit or channel systems can be lowered by reducing the moisture content of the manure by ventilating the manure pit.

104. The collection of manure on belts and the subsequent removal of manure to covered storage outside the building can also reduce NH_3 emissions, particularly if the manure has been dried on the belts through forced ventilation. The manure should be dried to 60%–70% DM to minimize the formation of NH_3. Manure collected from the belts into intensively ventilated drying tunnels, inside or outside the building, can reach 60%–80% DM content in less than 48 hours, but in this case exposure to air and emissions are increased. Weekly removal from the manure belts to covered storages reduces emissions by 50% compared with bi-weekly removal. In general, emission from laying hen houses with manure belts will depend on: (a) the length of time that the manure is present on the belts; (b) the drying systems; (c) the poultry breed; (d) the ventilation rate at the belt (low rate = high emissions); and (e) the feed composition. Aviary systems with manure belts for frequent collection and removal of manure to closed storages reduce emission by more than 70% compared with the deep litter housing system.

105. Treatment of exhaust air by acid scrubber or biotrickling filters has been successfully employed in several countries (Melse and Ogink, 2005; Ritz and others, 2006; Patterson and Adrizal, 2005; Melse, Hofschreuder and Ogink, 2012). Acid scrubbers remove 70%–90% of NH_3, while biological scrubbers remove 70%; both also remove fine dust and odour. To deal with the high dust loads, multistage air scrubbers with prefiltering of coarse particles have been developed (Ogink and Bosma, 2007; Melse, Ogink and Bosma, 2008). Yet some Parties consider this technique as only category 2 because of the dust loading issue.

106. Emission reduction techniques are summarized for conventional cage housing (table 8), for enriched caged housing (table 9) and for non-caged housing (table 10).

Category 2 techniques

107. The regular addition of aluminium sulphate (alum) to the litter in non-caged housing systems decreases NH_3 emissions from the buildings by up to 70%, and reducing also in-house concentrations of both NH_3 and fine particulate matter ($PM_{2.5}$) thus improving production. The alum also lowers phosphorus leaching losses from land-applied manure. Studies in the United States of America show that the benefits of alum treatment are twice the cost, but as there is no experience yet in other countries, this technique is considered category 2.

Table 8
Caged housing systems for laying hens (reference system): techniques and associated NH_3 emission reduction potential

Category 1	*kg NH_3/ year/place*	*NH_3 reduction (%)*	*Extra cost (€/place/year)*	*Cost (€/kg NH3-N abated/year)*
Conventional cages, non-aerated open manure storage under cages *(reference technique)*	0.1–0.2	—	—	—
Conventional cages, aerated open manure storage under cages to dry manure	—	30	—	0–3
Conventional cages, rapid manure removal with belt to closed manure storage	—	50–80	—	0–5
Scrubbing of exhaust air[a]	—	70–90	—	1–4

Note: For economic cost of the abatement techniques, see Reis (forthcoming).

[a] With acid scrubbers 70%–90% reduction can be achieved, with biological scrubbers 70%; some experts consider this category 2.

Table 9

Enriched cage housing systems for laying hens: techniques and associated NH_3 emission reduction potential

Category 1	*kg NH_3/ year/place*	*NH_3 reduction (%)*	*Extra cost (€/place/year)*	*Cost (€/Kg NH_3-N abated/year)*
Belts, two removals a week *(reference technique)*	0.05–0.1	—	—	—
Ventilated belts, two removals a week[a]	—	30–40	0	0
Ventilated belts, removals more than two times a week	—	35–45	—	0–3
Scrubbing of exhaust air[b]	—	70–90	—	2–5

Note: For economic cost of the abatement techniques, see Reis (forthcoming).

[a] Reduction percentage depending on ventilation rate of drying fan.

[b] With acid scrubbers 70%–90% reduction can be achieved, with biological scrubbers 70%; some experts consider this category 2.

Table 10

Non-caged housing systems for laying hens: techniques and associated NH_3 emission reduction potential

Category 1 and 2 techniques	*kg NH_3/ year/place*	*NH_3 reduction (%)*	*Extra cost (€/place/year*	*Cost (€/Kg NH_3-N abated/year)*
Deep litter or deep pit with partial litter (*reference technique*)	0.3	—	—	—
Aviaries, perch design, non-ventilated manure belts (cat. 1)	—	70–85	—	1–5
Aviaries, ventilated manure belts (cat. 1)	—	80–95	—	1–7
Scrubbing of exhaust air [a]	—	70–90	—	6–9
Litter, partly slatted, manure belts (cat. 2)	—	75	—	3–5
Litter with forced manure drying (cat. 2)	—	40–60	—	1–5
Regular addition of aluminium sulphate to litter (cat. 2)	—	70	—	?

Note: For economic cost of the abatement techniques, see Reis (forthcoming).

[a] with acid scrubbers 70%–90% reduction can be achieved, with biological scrubbers 70%; some experts consider this category 2.

2. Housing systems for broilers

108. *Reference system for broilers*: The reference system for broilers is the traditional building used in Europe with a solid, fully littered floor.

109. To minimize NH_3 emission in broiler housing, it is important to keep the litter dry. Litter moisture and emissions are influenced by:

(a) Drinking-water design and function (leakage and spills);

(b) Animal weight and density, and duration of the growing period;

(c) Ventilation rate, use of in-house air purification and ambient weather;

(d) Use of floor insulation;

(e) Type and amount of litter;

(f) Feed.

Category 1 techniques

110. *Reducing spillage of water from the drinking system*: A simple way to reduce spillage of water from the drinking system is using a nipple instead of bell drinkers.

111. *Air scrubber technology* to remove NH_3 from ventilation air is highly effective, but not widely implemented because of costs. Packed-bed filters and acid scrubbers currently available in the Netherlands and Germany remove 70%–90% of NH_3 from exhaust air. Questions about long-term reliability due to high dust loads lead some Parties to consider this as category 2 only. Various multi-pollutant scrubbers have been developed to also remove odour and particulate matter (PM_{10} and $PM_{2.5}$) from the exhaust air (Zhao and others, 2011; Ritz and others, 2006; Patterson and Adrizal, 2005).

Category 2 techniques

112. *Forced drying*: Effective emission reduction can be achieved through forced drying, but current systems are energy intensive and may increase dust emissions. However, there may be some saving in heating costs due to improved heat distribution.

113. *Combideck system*: This system consists of heat exchangers in the concrete floor. In the beginning of the fattening period the floor is heated to dry the litter and later in the fattening period the floor is cooled to reduce microbial activity, which reduces breakdown of uric acid. Because the effectiveness of this technique depends on local conditions it is considered as category 2.

114. Use of additives (aluminium sulphate, micro-organisms) may reduce NH_3 emissions, lead to a higher dry matter content of the manure and reduce mortalities (Aubert and others, 2011), but results are either inconsistent (e.g., McCrory and Hobbs, 2001), or tested in one country only (in the case of addition of aluminium sulphate).

3. Housing systems for turkeys and ducks

115. *Reference system for turkeys:* Reference system for turkeys for fattening is the traditional building used in Europe with solid, fully littered floor in closed, thermally insulated buildings with forced ventilation (as broilers) or in naturally ventilated houses with open sidewalls. Manure is removed at the end of each growing period. Ammonia emission with a fully littered floor is 0.680 kg NH_3-N per turkey place per year. Turkeys are a minor source of NH_3 in most ECE countries.

116. *Reference system for ducks:* The reference system for ducks is a traditional building similar to housing for broilers. Ducks for roasting generate slurry and ducks for “foie gras” generate solid manure. Partly slatted/partly littered floors and fully slatted floors are other housing systems for fattening of ducks. Like turkeys, ducks are a minor source of NH_3 in the ECE region.

117. Ammonia emission reducing techniques used for broiler production can be applied to turkey and duck housing. However, except for scrubbers, the efficacy of the techniques will be less than with broilers because of the larger amount of manure and a higher DM content of the litter. In the Netherlands, the effectiveness is considered half of that in broiler housing. For ducks provided with water bowls (in consideration of the welfare of water birds) efficacy may be even lower. Therefore, these techniques are considered category 2.

Table 11

Housing systems for broilers: techniques and associated NH_3 emission reduction potential

Category 1 and 2 techniques	*kg NH_3/ year/place*	*NH_3 reduction (%)*	*Extra cost (€/place/year)*	*Cost (€/Kg NH_3-N abated/year)*
Deep litter; fan-ventilated house (*reference technique*)	0.080	—	—	—
Naturally ventilated house or insulated fan-ventilated house with a fully littered floor and equipped with non-leaking drinking system (cat. 1)	—	20–30	—	—
Litter with forced manure drying using internal air (cat. 1)	—	40–60	—	2–4
Scrubbing of exhaust air (cat. 1)[a]	—	70–90	—	10–15
Tiered floor and forced air drying (cat. 2)	—	90	—	?
Tiered removable sides; forced air drying (cat. 2)	—	90	—	?
Combideck system (cat. 2)	—	40	—	6

Note: Data on economic costs of low-emission housing systems are scarce, also because there are often only few of these systems in practice yet. For economic cost of the abatement techniques, see Reis (forthcoming).

[a] With acid scrubbers 70%–90% reduction can be achieved, with biological scrubbers 70%; some experts consider this category 2.

Chapter 6

Manure storage techniques

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118. *Reference technique:* The baseline for estimating the efficiency of an abatement measure is the emission from the same type of store, without any cover on the surface. Baseline emissions are assumed to be 1.4 and 2.7 kg NH_3-N per m^2 per year based on data from Western European countries; lower values might be observed where stored manure is frozen for several months, and higher values in warm countries. Since baseline data are limited, Parties are encouraged to determine appropriate baseline values for their conditions. Table 12 summarizes the different emission abatement measures for slurry stores and their efficiency in reducing NH_3 emissions.

119. After removal from animal houses, slurry is commonly stored in concrete or steel tanks or silos, or in lined, earth-banked lagoons. Lagoons tend to have a larger surface area per unit volume than tanks and there is recent evidence of intense natural chemical denitrification in large lagoons due in part to wind action. Emissions from slurry stores can be reduced by decreasing the airflow across the surface by installing solid or floating covers, by allowing the formation of a surface crust, or by increasing the depth of stores to reduce the ratio of surface area to volume of the stores. Reducing the surface area is only a consideration for new structures. Co-benefits: solid covers (and open roofs) prevent rain from filling the storage so there is more predictable capacity and, with less water, hauling costs are lower; covers reduce odour and most also reduce greenhouse gas emissions, although under some conditions straw cover may increase emission of N_2O; reducing the surface to volume ratio tends to have the same co-benefits as covers.

120. For long-term storage of dry poultry manure (e.g., from broiler housing), a barn or building with an impermeable floor and with sufficient ventilation should be used to keep the manure dry and minimize further NH_3 losses.

121. It is important to minimize also the possible NH_3 losses during land spreading of the slurries and manure from covered storages, otherwise the benefits of the covered storage will evaporate like the NH_3.

Category 1 techniques

122. *"Tight" lid, roof or tent structure*: The best proven and most practicable method to reduce emissions from slurry stored in tanks or silos is to cover it with a "tight" lid, roof or tent structure. While it is important that such covers are well sealed or "tight" to minimize air exchange, some venting must be provided to prevent the accumulation of flammable gases, especially methane. The ability to retrofit these structures on existing stores depends on the structural integrity of the stores or whether they can be modified to accept the extra load.

123. *Floating cover:* Floating cover sheeting may be a type of plastic, canvas, geotextile or other suitable material. It is considered to be a category 1 technique only for small earth-banked lagoons. Floating covers are difficult to implement on tanks, especially those with high sides, because of the substantial vertical movement needed during filling and emptying.

124. *Storage bags* are suitable for reducing emissions from slurry on small farms (e.g., < 150 fattening pigs); note that the cost of this measure includes both the storage structure and the cover.

125. *Formation of natural crust*: Minimizing stirring of stored cattle slurry and some pig slurries (depending on diet of the pits and the DM content of the slurry) and introducing new slurry below the surface will allow the build-up of a natural crust. Crusts can significantly reduce NH_3 emissions at little or no cost for the time that the crust is sufficiently thick and fully covers the slurry surface. The emission abatement efficiency will depend on the nature and duration of the crust (Misselbrook, and others, 2005a; Smith and others, 2007). Abatement with natural crust is an option only for farms that do not have to frequently mix the manure for frequent spreading, and do have slurries that produce crusts.

126. Light expanded clay aggregates (LECA) balls and Hexa-Covers can be easily applied to non-crusting pig manure or digestate from anaerobic digesters. A recent review of abatement methods (van der Zaag and others, 2012) proposes that these are category 1 since they are not subject to many of the issues associated with sheets, such as water collection and tearing. In addition, they are easy to apply.

127. *Replacement of lagoons by tanks/silos:* If shallow earth-banked lagoons are replaced by deeper tanks or silos, emissions will be proportionately reduced due to the reduced surface area per unit volume. This could be an effective (though expensive) NH_3 reduction option, particularly if the tanks are covered by a lid, roof or tent structure (category 1 techniques). The cost-effectiveness of this option is difficult to quantify, as it depends strongly on the characteristics of the lagoon and the tank. Mixing manure in tall structures is difficult.

Category 2 techniques

128. *Floating covers (for stores other than small earth-banked lagoons):* There is a range of floating cover types made from permeable and impermeable materials that can reduce NH_3 emissions from stored slurries by restricting contact between the slurry and the air. However, the effectiveness and practicality of these covers is still uncertain except for well tested plastic sheeting on small earth-banked lagoons, and are likely to vary according to management and other factors. Examples include plastic sheeting, chopped straw and peat. Impermeable floating covers need venting and a method to remove rain water that gathers on top. Permeable floating covers must be carefully secured against the wind and both types must allow for vertical movement during filling and emptying. The durability of floating covers is not well tested. Floating covers might hinder homogenization of the slurry prior to spreading or hinder the spreading process itself. This aspect needs technical attention and optimization.

129. *Covering farmyard manure*: There are few options for reducing NH_3 emissions from stored farmyard (solid) manures for cattle and pigs. Experiments have shown that covering farmyard manure piles with plastic sheeting can substantially reduce NH_3 emissions and with no significant increase in methane or nitrous oxide emissions (Chadwick, 2005; Hansen, Henriksen and Sommer, 2006). At present, this is considered as a category 2 technique, due to the need for more general testing of abatement efficiency and practicability.

Table 12

Ammonia emission abatement measures for cattle and pig slurry storage

Abatement measure	*NH_3 emission reduction (%)*	*Applicability*	*Costs (OPEX) (€ per m^3/yr)[a]*	*Extra costs (€/kg NH_3-N reduced)[a]*
Store with no cover or crust (*reference technique*)	0		—	—
"Tight" lid, roof or tent structure (cat. 1)	80	Concrete or steel tanks and silos. May not be suitable for existing stores.	2–4	1.0–2.5
Plastic sheeting[b] (floating cover) (cat. 1)	60	Small earth-banked lagoons.	1.5–3	0.6–1.3
Allowing formation of natural crust by reducing mixing and manure input below the surface (floating cover) (cat. 1)	40	Only for slurries with higher content of fibrous material. Not suitable on farms where it is necessary to mix and disturb the crust in order to spread slurry frequently. Crust may not form on pig manure in cool climates.	0	0
Replacement of lagoon, etc., with covered tank or tall open tanks (depth > 3 m) (cat. 1)	30–60	Only new build, and subject to any planning restrictions concerning taller structures.	15 (about 50% cost of tank)	—
Storage bag (cat. 1)	100	Available bag sizes may limit use on larger livestock farms.	2.50 (includes cost of storage)	—
Floating LECA balls, Hexa-Covers (cat. 1)	60	Not suitable for crusting manures	1–4	1–5
Plastic sheeting[b] (floating cover) (cat. 2)	60	Large earth-banked lagoons and concrete or steel tanks. Management and other factors may limit use of this technique.	1.50–3	0.5–1.3
"Low technology" floating covers (e.g., chopped straw, peat, bark, etc.) (cat. 2)	40	Concrete or steel tanks and silos. Probably not practicable on large earth-banked lagoons. Not suitable if materials likely to cause slurry management problems.	1.50–2.50	0.3–0.9

Note: For economic cost of the abatement techniques, see Reis (forthcoming).

[a] Calculated for storage of pig slurry in stores ranging from 500 to 5,000 m³ capacity for temperate regions of Central Europe. The reference is slurry with no crust.

[b] Sheeting may be a type of plastic, canvas or other suitable material.

Chapter 7

Manure application techniques

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130. *Reference technique*. The reference manure application technique is defined as untreated slurry or solid manure spread over the whole soil surface ("broadcast") and not followed by incorporation, and not targeting application timing conditions that minimize NH_3 loss. For slurry, for example, this would typically consist of a tanker equipped with a discharge nozzle and splash-plate. For solid manures, the reference case would be to leave the manure on the soil surface without incorporation.

131. Emissions of NH_3 from the reference technique expressed as a percentage of the TAN applied are typically in the range of 40%–60% (although emissions outside this range are also common). Emissions will vary with the composition of the slurry or solid manure and with prevailing weather and soil conditions. Emissions of NH_3 as a percentage of TAN applied are normally decreased with decreasing evapotranspiration (air temperature, wind speed, solar radiation) and slurry DM concentration. Emissions of NH_3 as a percentage of TAN applied are normally decreased with increasing TAN concentration and application rate. Emissions from different manure types will also vary. Emissions are also dependent on soil conditions that affect infiltration rates. For example, well-draining, coarse textured, dry soils, which allow faster infiltration, will give rise to lower emissions than wet and compact soils with reduced infiltration rate (Søgaard and others, 2002). However, when very dry, some soils may become hydrophobic, which can also reduce infiltration and therefore increase emissions.

132. *Specification of abatement efficiency*. Emissions will vary with the composition of the slurry and solid manure and with prevailing weather and soil conditions. Abatement efficiencies will also vary relative to reference emissions depending on these factors. For this reason, the figures quoted in table 14 represent averages from many studies in different countries over a wide range of conditions. The absolute magnitude of NH_3 emission levels of the reference techniques varies temporally and at a regional scale in response to variation in environmental conditions. While these factors also affect the absolute magnitude of NH_3 emissions from low-emission approaches, the relative emission levels are comparable; for this reason the benefits of using low-emission approaches are expressed as percentage reduction compared with the reference.

133. Category 1 techniques include machinery for substantially decreasing the exposed surface area of slurries applied to the surface of soil or burying slurry or solid manures through injection or incorporation into the soil. The economic costs of these techniques are in the range €0.1 to €5 per kg NH_3-N saved, with the smallest costs for immediate incorporation of slurries and solid manure, where this is feasible (i.e., on bare arable land). The estimates are very sensitive to assumed farm size, with substantially improved economies of scale on larger farms, where low-emission equipment is shared between several farms, or where specialist contractors are used. The techniques included in category 1 are:

(a) Band spreading slurry on the soil surface using trailing hose or trailing shoe methods;

(b) Injecting slurry — open slot;

(c) Injecting slurry — closed slot;

(d) Incorporation of surface-applied solid manure and slurry into soil;

(e) Dilution of slurry by at least 50%, when applied in low pressure water irrigation systems.

134. The average NH_3 abatement efficiencies of category 1 techniques, relative to the reference, and an indication of the cost of each technique relative to the reference are given in table 13 for slurries and in table 15 for solid manures.

135. Efficiency levels for techniques (a)-(c) is valid for soil types and conditions that allow infiltration of liquid and satisfactory travelling conditions for the machinery.

136. Tables 13 and 14 also summarize the limitations that must be taken into account when considering the applicability of a specific technique. These factors include: soil type and condition (soil depth, stone content, wetness, travelling conditions); topography (slope, size of field, evenness of ground); and manure type and composition (slurry or solid manure). Some techniques are more widely applicable than others. Additional costs are negligible, if the ploughing or soil cultivation has to be done anyway, but for emission mitigation this has to be done directly after application, which may require additional resources.

137. Techniques (a)-(c) operate on the basis that the surface area of slurry exposed to the prevailing weather conditions is reduced by at least 75% through confining the slurry to lines/bands, which are approximately 250 (+/- 100) millimetres (mm) apart. The slurry is distributed through a number of relatively narrow pipes (usually 40–50 mm diameter). These machines usually incorporate systems for filtering, chopping and homogenizing slurry, which minimize the occurrence of blockages in narrow pipes caused by slurries that are very viscous or that contain large amounts of fibrous material or foreign objects, such as stones. Band-spreading and injection systems are normally fitted to the rear of slurry tankers, which are either towed by a tractor or form parts of self-propelled machines. An alternative is for the application system to be attached directly to the rear of a tractor and slurry transported to it by an “umbilical” hose from a stationary tanker or store. Such umbilical systems can reduce soil compaction damage caused by heavy slurry tankers.

138. **Band spreading slurry on or above the soil surface.** Band spreading on or above the soil surface can be carried out using implements commonly referred to as “trailing hose” (also known as “drag hose” and “drop hose”) and “trailing shoe” (also known as “drag shoe” and “sleighfoot”). Trailing shoe and trailing hose systems are distinguishable from each other through the presence (trailing shoe) or absence (trailing hose) of a “shoe” or “foot” device at the outlet of each slurry distribution-application pipe which slides (or floats) on the surface of the ground with little or no penetration. The hose or shoe is intended to part the herbage or any crop residue present to allow slurry placement directly on the soil surface. The greater efficiency generally reported with the sliding shoe (J. Webb and others, 2010) is attributed to manure being in narrower bands, having more contact with the soil and having less contact with live or dead vegetative material because it is better pushed aside by the shoe than the hose, even if the hose is very close to the ground. The benefit of the shoe compared with the hose is greatest for taller canopies because of the reduced degree of canopy contamination. Both systems are usable in a range of cropping situations, although of the two the hoses are less restrictive because they can be more widely used in standing crops without damage and are amenable to tramline systems. Both systems apply manure more uniformly, and are less susceptible to wind, compared with the reference system. They increase the time available for spreading and allow spreading closer to field margins with a low risk of contaminating adjacent areas.

139. **Trailing hose.** This technique discharges slurry at or just above ground level through a series of hanging or trailing pipes or flexible hoses, which either hang a short distance (< 150 mm) above the soil or are dragged along the soil surface. The working width is typically between 6 and 12 metres (m), although larger units of up to 24-m width are commercially available. The possible working width (requiring manual or powered swing arms for transport) is much larger than for the “splash-plate” reference system (6–9 m), representing a clear advantage of the trailing hose method. The spacing between bands (centre to centre) is typically 250–350 mm. The technique is applicable to grass and arable crops, and can be used with tramlines. The pipes may become clogged if the DM content of the slurry is high (> 7%–10%) or if the slurry contains large solid particles. However, the clogging of pipes is usually avoided by including a chopping and distribution system. This system improves spreading uniformity which improves nutrient use, but contributes significantly to the cost and maintenance of the system. The chopper/ distributor device can often be designed and built locally so that the costs may be quite low.

Table 13

Category 1 abatement techniques for slurry[11] application to land

Abatement measure	*Land use*	*Emission reduction (%)*[a]	*Factors affecting emission reduction*	*Applicability compared with the reference*	*Cost (€/Kg NH_3 abated/year)*
(a) (i) Band spreading slurry with a trailing hose	Arable/ grassland	30–35	More crop canopy will increase reduction, depending on placement precision and the extent of herbage contamination.	Less suitable where slope > 15%. Can be used on solid seeded crops and wide units may be compatible with tramlines.	-0.5–1.5 (note that the costs may be reduced if the equipment is locally designed and built)
(a) (ii) Band spreading with trailing shoe	Arable/ grassland (pre-seeding) and row crops	30–60	More crop canopy will increase reduction, depending on placement precision and the extent of herbage contamination.	Not suitable for use in growing solid seeded crops but may be possible to use in the rosette stage and for row crops.	-0.5–1.5
(b) Injecting slurry (open slot)	Grassland	70	Injection depth ≤ 5 cm	Unsuitable where: slope > 15%; high stone content; shallow soils; high clay soils (> 35%) in very dry conditions; and peat soils (> 25% organic matter content). Tile-drained soils susceptible to leaching.	-0.5–1.5
(c) Injecting slurry (closed slot)	Arable/ grassland	80 (shallow slot 5–10 cm) 90 (deep injection > 15 cm)	Effective slit closure	Unsuitable where: slope > 15%; high stone content; shallow soils; high clay soils (> 35%) in very dry conditions; and peat soils (> 25% organic matter content). Tile-drained soils susceptible to leaching.	-0.5–1.2

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[11] Slurry is defined as flowable manure usually less than 12% DM. Material with a higher DM content or containing high amounts of fibrous crop residue may require pre-treatment (e.g., chopping or water addition) to be applied as a slurry, and should otherwise be handled as for solid manures (table 15). Costs assume medium or high usage of equipment. Where a low use is made of the relevant equipment, costs per unit N saved may be higher.

Table 13 (Continued)

Category 1 abatement techniques for slurry application to land

Abatement measure	*Land use*	*Emission reduction (%)*[a]	*Factors affecting emission reduction*	*Applicability compared with the reference*	*Cost (€/Kg NH_3 abated/year)*
(d) Incorporation of surface applied slurry	Arable	Immediately by ploughing = 90			-0.5–1.0
		Immediately by non–inversion cultivation (such as discing) = 70			-0.5–1.0
		Incorporation within 4 hrs = 45–65	Efficiency depends on application method and weather conditions between application and incorporation.	Efficiency depends on application method and weather conditions between application and incorporation.	-0.5–1.0
		Incorporation within 24 hours = 30	Efficiency depends on application method and weather conditions between application and incorporation.	Efficiency depends on application method and weather conditions between application and incorporation.	0–2.0
(e) Active dilution of slurry of > 4% DM to < 2% DM for use in water irrigation systems	Arable/ Grassland	30	Emission reduction is proportional to the extent of dilution. A 50% reduction in DM content is necessary to give a 30% reduction in emissions.	Limited to low pressure water irrigation systems (not "big guns"). Not appropriate where irrigation is not required.	-0.5–1.0

Note: The abatement measures refer to the category 1 techniques listed in paragraph 133.

[a] Average emission reductions agreed to be achievable across the ECE region. The wide ranges reflect differences in techniques, management, weather conditions, etc.

Table 14

Category 1 abatement techniques for solid manure[12] application to land

Abatement measure	*Land use*	*Emission reduction (%)*[a]	*Factors affecting emission reduction*	*Limitations to applicability compared with the reference*	*Cost (€/Kg NH_3 abated/year)*
Incorporation of surface applied manure	Arable	Immediately by ploughing = 90	Degree of burying the manure	—	-0.5–1.0
		Immediately by non-inversion cultivation = 60	Degree of burying the manure	—	0–1.5
		Incorporation after 4 hrs = 45–65	Degree of burying the manure. Efficiency depends on time of day of spreading and weather conditions between application and incorporation.	Degree of burying the manure. Efficiency depends on time of day of spreading and weather conditions between application and incorporation.	0–1.5
		Incorporation within 12 hours = 50	Degree of burying the manure. Efficiency depends on time of day of spreading and weather conditions between application and incorporation.	Degree of burying the manure. Efficiency depends on time of day of spreading and weather conditions between application and incorporation.	0.5–2.0
		Incorporation within 24 hours = 30	Degree of burying the manure. Efficiency depends on time of day of spreading and weather conditions between application and incorporation.	Degree of burying the manure. Efficiency depends on time of day of spreading and weather conditions between application and incorporation.	0.5–2.0

[a] Emissions reductions are agreed as likely to be achievable across the ECE region.

141. The NH_3 emission abatement potential of trailing shoe or trailing hose machines is more effective when slurry is applied below well-developed crop canopies rather than on bare soil, because the crop canopy increases the resistance to air turbulence from wind and shades the slurry from solar radiation. In general, NH_3 emission reductions have typically been found to be larger from trailing shoe than from trailing hose, which is most likely due to the higher degree of canopy contamination resulting from certain types and implementation of the trailing hose methods. This emphasizes the need to avoid canopy contamination with slurry when using either method, which also has benefits for herbage quality.

142. **Injection — open slot.** This technique is mainly for use on grassland or minimum till cropland prior to planting. Different shaped knives or disc coulters are used to cut vertical slots in the soil up to 50 mm deep into which slurry is placed. Spacing between slots is typically 200–400 mm and machine working width is typically ≤6 m. To be effective in both reducing NH_3 emissions and increasing the availability of N to the crop, while also reducing crop injury, injection should be to a depth of approximately 50 mm and the space between injector tines should be ≤ 300 mm. Also, the application rate must be adjusted so that excessive amounts of slurry do not spill out of the open slots onto the surface. The technique is not applicable on very stony soils, or on very shallow or compacted soils, where it is impossible to achieve uniform penetration to

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[12] Solid manure is defined as non-flowable manure usually with more than 12% DM.

the required working depth. The method may not be applicable on very steeply sloping fields due to the risk of run-off down the injection furrows. Slurry injection systems will have a higher tractor power requirement than broadcast or band-spreading equipment.

143. **Injection — closed slot.** This technique can be relatively shallow (50–100 mm depth) or deep (150–200 mm). Slurry is fully covered after injection by closing the slots with press wheels or rollers fitted behind the injection tines. Deeper injection is required when greater volumes of manure are injected to avoid the manure oozing to the surface. Shallow closed-slot injection is more efficient than open-slot in decreasing NH_3 emission. To obtain this added benefit, soil type and conditions must allow effective closure of the slot. The technique is, therefore, less widely applicable than open-slot injection. Some deep injectors comprise a series of tines fitted with lateral wings or "goose feet" to aid soil penetration and lateral dispersion of slurry in the soil so that relatively large application rates can be achieved. Tine spacing is typically 250–500 mm and working width ≤ 4 m. Although NH_3 abatement efficiency is high, the applicability of the technique is mainly restricted to pre-sowing application to arable land and widely spaced row crops (e.g., maize), while mechanical damage may decrease herbage yields on grassland or growing solid-seeded arable crops. Other limitations include soil depth, clay and stone content and slope, as well as a high tractor power requirement and increased risk of leaching, particularly on tile-drained soils.

144. **Incorporation of surface-applied solid manure and slurry into soil**. Incorporating surface applied manure or slurry by either ploughing or shallow cultivation is an efficient means of decreasing NH_3 emissions. The highest reduction efficiencies are achieved when the manure is completely buried within the soil (table 14). Ploughing results in higher emission reductions than other types of machinery for shallow cultivation. The applicability of this technique is confined to arable land. Incorporation is not applicable on permanent grassland, although it may be possible to use in grassland systems either when changing to arable land (e.g., in a rotation) or when reseeding pasture, although nutrient requirements may be low at both of these times. It is also less applicable to arable crops grown using minimum cultivation techniques compared with crops grown using deeper cultivation methods. Incorporation is only possible before crops are sown. The technique is the main technique applicable to achieve emission reductions from application of solid manures on arable soils, although new applicators for injecting poultry litter into sod are being tested in North America. It is also effective for slurries where closed-slot injection techniques are not possible or available or present a risk of leaching. Cultivation also reduces macropores which can facilitate leaching. The success of this approach has been shown in many studies, including in the Russian Federation (Eskov and others, 2001).

145. Ammonia loss takes place quickly (over several hours and days) after manures are spread on the surface, so greater reductions in emissions are achieved when incorporation takes place immediately after spreading. Immediate incorporation often requires a second tractor to be used for the incorporation machinery, which must follow closely behind the manure spreader. Where labour or machinery requirements limit this option, such as for small farms, manures should be incorporated within four hours of spreading, but this is less efficient in reducing emissions (table 14). Incorporation within 24 hours of spreading will also reduce emissions to an even smaller extent, but increases agronomic flexibility, which may be especially important for small farms. It is most important to incorporate rapidly when manure is applied near midday in hot conditions. It may be possible to spread and incorporate with a single implement. This can work well, provided that less than 25% of the manure is left exposed to the atmosphere.

146. **Slurry dilution for use in irrigation systems.** Ammonia emissions from dilute slurries with low DM content are generally lower than for whole (undiluted) slurries because of faster infiltration into the soil (e.g., Stevens and Laughlin, 1997; Misselbrook and others, 2004). Doses of slurry, calculated to match the nutrient requirement of crops, can therefore be added to irrigation water to be applied onto grassland or growing crops on arable land. Slurry is pumped from the stores, injected into the irrigation water pipeline and brought to a low pressure sprinkler or travelling irrigator (not big gun with high pressure), which sprays the mix onto land. Dilution rates may be up to 50:1 water:slurry. This approach is included as a category 1 method so far as this is an active dilution for use in water irrigation systems with a dilution of at least 50% (1:1 water:slurry) sufficient to reduce emissions by at least 30%, where there is a need for water irrigation. In the case of slurry with a DM content of 4%, this would need to be diluted to ≤ 2% DM content (see figure 1). In order to be considered a category 1 method, the following conditions should apply:

(a) The slurry is actively diluted for use in irrigation systems by at least the required amount of 1:1 dilution with water. By contrast, the slurry should not simply be diluted through poor management practice, such as because of slurry storage in shallow uncovered lagoons that collect a lot of rainwater. These storages are discouraged because they are in themselves potentially significant sources of emissions that are difficult to control with covers;

(b) Conditions are suitable for irrigation to meet crop water needs. Dilution of slurry without a water need adds to hauling costs and may exacerbate nitrate leaching;

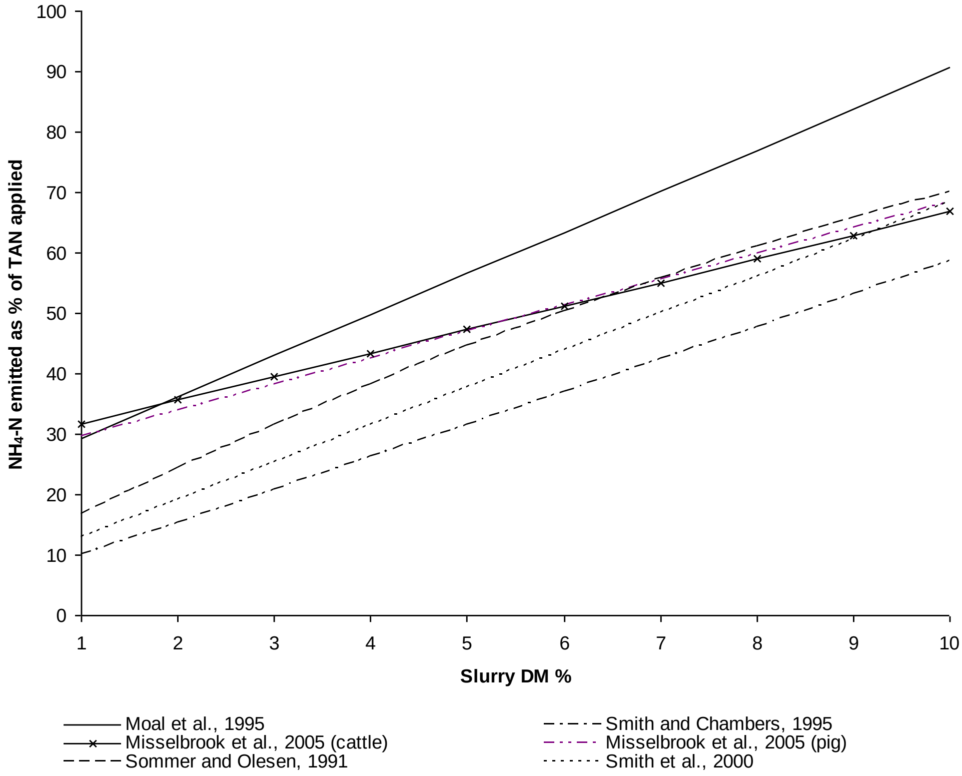
(c) The amounts of slurry applied are calculated to match nutrient needs. The method should not be seen as an easy option for slurry disposal, with the possible risk of over fertilization and nitrate leaching or manure run-off, especially on sloped fields;

(d) Soil conditions allow for rapid soaking of dilute slurries because there are no physical impediments to infiltration, such as high soil water content, poor soil structure, fine texture or other soil attributes that reduce infiltration rates of liquids into soil, and there is no decrease in infiltration rate due to high application volumes.

147. In addition to the specific dilution of slurry in irrigation systems, other methods of reducing slurry DM content can provide a useful means to reduce NH_3 emissions. These include reducing DM levels through anaerobic digestion and by solid-liquid separation. Because such methods can tend to increase the pH of the low DM fraction and also produce a sludge with higher DM content, they are not included as category 1 methods. Such methods can, nevertheless, provide a useful approach as part of category 2 methods, where verification of the emission reductions should be provided.

Figure 1

Relationship between the percentage of TAN emitted as NH_3 during the land application of slurry and the DM content (DM% weight) of the slurry, according to six estimates



Note: Even though NH_3 emissions are still significant at 1% DM content (10-30% of TAN lost through volatilisation), a 50% reduction in DM content will achieve roughly a 30% reduction in average NH_3 emissions.

148. **Additional benefits of techniques to reduce NH_3 emissions from the land application of slurry and solid manure**. The experimental quantification of increased manure N efficiency associated with reduced NH_3 emissions has given variable results (J. Webb and others 2010). This may be partly explained

by the difficulty implicit in any attempt to detect a significant crop response to low-N fertilizer additions against relatively large background soil N-mineralization rates. In practice, the reduction in NH_3 emission translates into a reduction of application rate of additional N. Although the uptake of the NH_3-N by the crop will vary, the TAN that is not volatilized can be considered as potentially equivalent to chemical N fertilizer. Therefore, reduced NH_3 losses can be considered to replace chemical fertilizer applications on a 1:1 ratio.

149. Band-spreading and injection techniques, as well as the rapid incorporation of solid manures, considerably reduce the odour associated with manure application. The reduction in odour emissions achieved by these techniques can allow application on areas or at times that may otherwise be unavailable due to complaints.

150. Band-spreading and injection techniques can allow more accurate slurry application rates than the reference technique, as the slurry should be distributed in equal proportions to pipes that are equally spaced apart along a fixed bout width. By comparison, the spatial distribution following application using the splash-plate applicator (the reference system) is often more variable, depending on the design and condition of the splash-plate unit. Also, the bout width using splash-plates can be more variable (e.g., affected by wind), resulting in imperfect alignment of adjacent bout strips and less accurate application along field boundaries. This potential improvement in the accuracy of application increases the efficiency of slurry as a nutrient source. The improvement in application accuracy also reduces the risk of nitrate, phosphorus and microbial pollution by avoiding spreading slurry onto adjacent areas such as near watercourses.

151. The window of opportunity for slurry application using the reference technique (broadcast spreading) is restricted by the risk of crop quality deterioration or damage caused by slurry contamination. Band spreading and injection reduce the occurrence of herbage contamination and therefore increase the crop canopy height onto which slurry can be applied without threatening crop quality. This is particular relevant to grassland, where slurry contamination can reduce grazing palatability or silage quality and may transfer pathogens (e.g., Johne’s disease) between farms if manure or equipment is shared. These methods also allow slurry application on growing arable crops (particularly cereals) which are generally not considered suitable to receive slurry applied using a splash-plate. The use of low-emission techniques can therefore help to increase the flexibility of slurry application management by allowing more land area to be available on days when weather conditions are more suitable for reduced NH_3 volatilization and optimal slurry-N utilization, and when soil moisture conditions are suitable to allow machinery traffic with minimal soil compaction.

152. **Potential cost implications of abatement techniques.** Cost increases associated with purchasing and maintaining, or hiring contractors with, new application machinery can be a disincentive to the adoption of abatement techniques. Injection techniques also require higher tractor power, further adding to the cost of adoption for those systems. These additional costs can be partially or totally outweighed by the financial benefit of improving yield and yield consistency, reducing N losses (by reducing mineral fertilizer requirements), by more precise delivery of manure-N to the crop, by the increased agronomic flexibility and by other co-benefits such as reduction of odour and crop contamination and improved visual aesthetics during and after manure application (J. Webb and others, 2010). The overall cost-benefit ratio depends especially on equipment costs and abatement efficiency.

153. **Impact of reduced ammonia losses on the N cycle.** If no crops are present, or growing, following manure application to take up the readily available N, the risk of N loss via leaching or gaseous N_2O increases. Hence incorporation and especially injection of manures involves a risk of exchanging air pollution for water pollution, but reduces the risk of surface run-off from subsequent rainfall events. For this reason, the timing of slurry and solid manure application needs to balance the potential for low NH_3 emissions against the other loss pathways, while considering the timing of crop needs. To avoid overall losses of N, manure should not be applied when there is no or very limited crop uptake. Ammonia mitigation makes an important contribution to the overall reduction of N losses from agriculture, thereby maximizing the agronomic benefits of applied mineral fertilizers. The financial benefit to the farmer of reducing the need for mineral N fertilizers is complemented by a regional-scale greenhouse gas benefit due to reduced mineral fertilizer needs, given the fertilizer-related N_2O emissions from soils and the high energy costs of N-fertilizer manufacture.

154. Results suggest that injection of slurry may either increase or have no impact on emissions of N_2O. The addition of readily degradable carbon (C) in slurry has been proposed as a mechanism responsible for increasing emissions of N_2O by more than would be expected, due to the additional N entering the soil as a result of NH_3 emission abatement. This addition of readily degradable slurry-C, without significantly aerating the soil, may increase denitrification activity. There are a number of reasons why reduced NH_3 emission

application techniques would not always lead to greater emissions of N_2O, such as: (a) deeper injection (> 5 cm) or incorporation, by increasing the length of the diffusion path from the site of denitrification to the soil surface, may lead to a greater proportion of denitrified N being emitted as N_2; (b) the subsequent soil moisture status, and hence aeration, may not be suitable for increased N_2O production; (c) in soils already well supplied with both readily degradable C and mineral N, any increase in N_2O emission may be too small to have a significant effect; and (d) the impact of subsequent weather on soil moisture content and water-filled soil pore space will also affect subsequent emissions of N_2O. The reflection of these interactions is that mitigation of NH_3 emissions reduces the N_2O emissions associated with atmospheric N deposition to semi-natural ecosystems and allows a saving of fertilizer inputs, leading to overall reduction in N_2O emissions.

155. Incorporation of FYM appears to reduce or have no impact on N_2O emissions. In contrast to slurry, there is evidence that readily degradable C is lost as part of the effluent arising during storage of solid manures. Hence the C added to soil by incorporation of solid manures will have less effect than slurry on microbial metabolism.

Category 2 techniques

156. **Verification of category 2 techniques.** Category 2 techniques may form a useful part of a package of measures to reduce NH_3 emissions, but may be more uncertain or the emission reductions inherently harder to generalize than for category 1. For this reason, this Guidance document specifies that, where category 2 methods are used to achieve the specified emission reductions, details should be provided by parties to verify the reported emission reductions from the methods. Such verification should also be provided for category 3 methods where these are used. For techniques based on (a) increasing the rate of infiltration into the soil and (b) pressurized injection of slurry, documentation should describe the practice used and give evidence from field- or farm-scale measurements demonstrating and justifying the emission reduction. Specific requirements apply to the verification of application timing management systems, as described in the paragraph below.

157. **Increasing rate of infiltration into the soil.** When soil type and conditions allow rapid infiltration of liquid, NH_3 emission decreases with decreasing slurry DM content. Dilution of slurry with water not only decreases the ammonium-N concentration, but also increases the rate of infiltration into the soil following spreading on land. For undiluted slurry (i.e., 8%–10% DM), dilution must be at least 1:1 (one part slurry to one part water) to reduce emissions by at least 30%. A major disadvantage of the technique is that extra storage capacity may be needed and a larger volume of slurry must be applied to land. In some slurry management systems, slurry may be already diluted (e.g., where milking parlour or floor washings, rainfall, etc., are mixed with the slurry) and there may be only a small advantage in actively diluting further. Extra cost for storage capacity and, mainly, for transport in land application, should discourage use of this technique. Also, there may be a greater risk of aquifer pollution, more water wastage and a greater carbon footprint because of the additional transport. Experience from the Russian Federation shows that pre-cultivation to increase infiltration (e.g., discing or slotting) provides a useful means to increase infiltration rate prior to slurry application (Eskov and others, 2001).

158. When applying diluted slurries to land there may be a greater risk of surface run-off and leaching, and this must be guarded against by paying attention to application rate, soil conditions, slope of the land, etc. For these reasons, apart from the active dilution of slurry for irrigation (category 1), this method is included as category 2.

159. Another means of decreasing slurry DM content, and hence increasing the rate of infiltration into the soil, is to remove a proportion of the solids by mechanical separation or anaerobic digestion. Using a mechanical separator with a mesh size of 1–3 mm reduces NH_3 loss from the separated liquid by a maximum of 50 per cent. Another advantage lies in reduced soiling of grass swards. Disadvantages of the technique include the capital and operating costs of the separator and ancillary equipment, the need to handle both a liquid and a solid fraction and emissions from the solids. Information to verify such systems should include demonstration of the overall NH_3 emission reduction, taking account of the emissions from both the low-DM and high-DM fractions.

160. A third option for increasing infiltration rate is to wash slurry off grass and into the soil by applying water after spreading. A plentiful supply of water is needed, the application of which is an additional operation, but Canadian results have shown that 6 mm of water can under some circumstances reduce NH_3 losses by 50 per cent compared with surface application alone. Information to verify such systems should

specify the time delay between slurry application and washing the grass with water, the amounts of water used and the percentage emission reduction achieved. When applying water after spreading, there may be a greater risk of surface run-off and leaching, depending on soil conditions, slope of the land, etc. For these reasons, apart from the active dilution of slurry for irrigation (category 1), this method is included as category 2.

161. **Pressurized injection of slurry.** In this technique, slurry is forced into the soil under pressure of 5–8 bars. Because the soil surface is not broken by tines or discs, the technique is applicable on sloping land and stony soils where other types of injector cannot be used. Emission reductions of typically 60 per cent, similar to that for open slot injection, have been achieved in field trials, but further evaluation of the technique is needed.

162. **Application timing management systems (ATMS)**. Ammonia emissions are highest under warm, dry, windy conditions (i.e., when evapotranspiration rates are high). Emissions can be reduced by optimizing the timing of application, i.e., cool, humid conditions, in the evenings, before or during light rain and by avoiding spreading during warm weather conditions, particularly during periods when solar elevation, and hence solar radiation input, is most intense (June/July) (Reidy and Menzi, 2007). This is potentially a cost-effective approach as it can be done using broadcast application equipment. The ATMS approach might also lead to an additional benefit when used in combination with a low-emission application technique, like the trailing hose. Potential emission reductions achievable through these measures will vary depending on regional and local soil and climatic conditions, and therefore the suite of measures that may be included will be specific to regional conditions.

163. While the benefits of using such timing management practices has long been known, the main constraints are:

(a) The need to demonstrate that the approach can deliver a specified NH_3 emission reduction target in practice;

(b) The need to carefully define what is meant by reference conditions (in order to ensure correct reporting of the outcomes);

(c) The need to implement a system to manage this approach that verifies its efficacy and implementation;

(d) Reduced flexibility when spreading manure with respect to soil trafficability, labour and equipment availability and consideration of other regulations.

164. This approach can be considered as rather different to the technical methods listed as category 1, such as band spreading and manure incorporation, where the efficiencies reported in tables 12 and 13 are based on the average outcomes from many studies. In the case of ATMS, the assessment uses the responses of models (based on many studies and accounting for meteorological conditions) to the actual timing practice.

165. In order to allow the benefits of timing practices to be included as an abatement measure, the above-listed constraints must be addressed. This can be achieved through the use of an ATMS, which is here defined as: *a verifiable management system for the direction and recording of solid and liquid manure application at different times, the adoption of which is demonstrated to show quantified farm-scale reductions in* NH_3 *emissions.* The use of any ATMS must demonstrate achievement of a specified NH_3 emission reduction target, by comparison with the reference, in order for its benefit to be considered as part of international emission control strategies.

166. ATMSs may be designed to exploit several principles in the variation of NH_3 emissions, the benefits of which will vary with local climate, so that ATMS implementation will vary regionally. The following principles may be exploited in an ATMS:

(a) **Weather-determined variation in NH_3 emissions.** Ammonia emissions tend to be smaller in cool and wet conditions and after light rain (though water-logging of soils can make spreading conditions unfavourable). Ammonia emissions can therefore be forecasted by coupling NH_3 emissions models with weather forecasting, as is already available in some countries, with land-application timing restricted to forecasted periods of low NH_3 emissions;

(b) **Seasonal variation in NH_3 emissions.** Ammonia emissions can be estimated on a seasonal basis by generalizing weather conditions for particular seasons. For example, seasonal variations lead to largest NH_3

emissions in warm summer conditions and smaller emissions in cool, moist winter conditions. Subject to other constraints, such as the objective to match manure application to the timing of crop needs, and the need to avoid water pollution, a targeted seasonal management of solid and liquid manure application has the potential to reduce overall annual NH_3 emissions;

(c) **Diurnal variation in NH_3 emissions.** Ammonia emissions tend to be smaller at night due to reduced wind speed, cooler temperatures and higher humidity;

(d) **The effect of timing of animal housing versus grazing on NH_3 emissions.** Ammonia emissions from livestock allowed to range outdoors with sufficient foraging area (e.g., cattle grazing) tend to be much smaller than for housed livestock, since this practice avoids NH_3 emissions associated with housing, manure storage and land spreading of slurries and solid manures. Therefore, subject to other constraints, such as water and soil quality issues arising from grazing during the winter, increasing the period in which animals are in the field (especially when 24 hours a day) can reduce NH_3 emissions. Changes in timing practice may be included in an ATMS since these affect the total amounts of manure to be spread.

167. **Verification procedures for ATMS.** One of the main challenges for any ATMS is to demonstrate an appropriate verification of the approach, particularly given the requirement to demonstrate the achievement of a specified emission reduction. The ATMS approach is considered most relevant at the farm scale, as it results from the overall outcome of a package of timing practices. The emission reduction target should be applied on an annual scale as the emission reduction potential of this method is time dependent.

168. Verification of an ATMS should include each of the following steps:

(a) **Verification of the core biophysical modelling tool used**. A transparent description of the numerical model used should be provided, underpinned by appropriate independent verification from field measurements;

(b) **Verification of the effect of a specific timing management on NH_3 emissions.** The degree to which the timing management leads to the target emission reduction required, as compared with the reference conditions for that region, should be demonstrated for any ATMS being used;

(c) **Verification that actual practices conform to those reported.** Any ATMS should be implemented in conjunction with an appropriate recording system, to ensure and demonstrate that the timing management recorded in the ATMS is being fully implemented.

169. **Definition of the reference conditions for an ATMS.** In the case of most low-emission techniques for land application, the percentage reduction achieved can be generalized over a wide climatic area. By contrast, where an ATMS is used, a more detailed definition of the reference conditions is needed. Overall, the same reference technique applies (free broadcast surface application of slurries and solid manures), but where an ATMS is used, the reference must also be defined on the farm level, according to existing practices. In order to account for regional variability in climate and inter-year variability in meteorological conditions, the reference condition for ATMS is extended to include: the combination of manure application management practices, and their timing, at a farm scale during a specified reference period, when using the reference application method (broadcast spreading), accounting for three-year variability in meteorological conditions.

170. The emission reduction potential of an ATMS should be verified for the region within which it is adopted. Numerical NH_3 emission simulation models will, in general, need to be used as part of the verification of ATMS.

171. An ATMS may be used in combination with other measures for reducing NH_3 emissions following land application of manures, such as slurry application technologies or incorporation of manures into soil. However, the additional absolute NH_3 emission reduction of an ATMS will vary depending on the emission reduction potential of the accompanying application method. The joint contribution of both low-emission application methods and an ATMS should be assessed to ensure that the overall farm-scale NH_3 reduction target is met.

172. Depending on the type of ATMS to be implemented, the main additional costs will be associated with reduced flexibility in timing of manure application, and the associated administrative costs necessary for the verification. Potential cost savings may be found by combining ATMS approaches with advice on managing farm N stocks more effectively, such as through a proven expert system.

173. Application prior to or during weather conditions that increase the risk of nutrient loss to waters should be avoided. Aspects of safety associated with machinery operation at certain times, particularly during hours of darkness, should also be considered when designing an ATMS. Conditions that favour reduced NH_3 emissions (e.g., humid, no wind) may give rise to problems with offensive odours by preventing their rapid dispersion.

174. **Acidified slurry.** The equilibrium between ammonium-N and NH_3 in solutions depends on the pH (acidity). High pH favours loss of NH_3; low pH favours retention of ammonium-N. Lowering the pH of slurries to a stable level of 6 and less is commonly sufficient to reduce NH_3 emission by 50 per cent or more. The technique of adding sulphuric acid to slurry is now practiced in Denmark, with considerable success. When adding acids to slurry, the buffering capacity needs to be taken into account, usually requiring regular pH monitoring and acid addition to compensate for carbon dioxide (CO_2) produced and emitted during the preparation of the acidified slurry. Acidification preferably has to be carried out during storage of slurry and also during spreading using specially designed tankers. Although efficient, the technique has the major disadvantage that handling strong acids on farms is very hazardous.

175. Options to achieve acidified slurry are by adding organic acids (e.g., lactic acid) or inorganic (e.g., nitric acid, sulphuric acid, phosphoric acid) or by the modifying or supplementation of animal feed (e.g., benzoic acid) (see section IV) or slurry of components (e.g., lactic acid-forming bacteria) that enhance pH reduction. Organic acids have the disadvantage of being rapidly degraded (forming and releasing CO_2); moreover, large quantities are required to achieve the desired pH level, since they are usually weak acids. Nitric acid has the advantage of increasing the slurry-N content so giving a more balanced nitrogen-phosphorus-potassium (NPK) fertilizer, but has the potential large disadvantage of nitrification, denitrification-mediated N_2O production and associated pH rise. A pH value of ~4 is required when using nitric acid to avoid nitrification and denitrification, causing loss of nitrate (NO_3) and production of unacceptable quantities of N_2O. Using sulphuric acid and phosphoric acid adds nutrients to the slurry that may cause over-fertilization with sulphur (S) and potassium (P). Moreover, adding too much acid could produce hydrogen sulphide and worsen odour problems and health and safety issues. Acidification of slurry to reduce NH_3 emissions is now used operationally in Denmark on 125 farms, where the pH of slurry is reduced from ~7.5 to ~6.5. This approach is used both in the stable (giving and estimated 70% reduction in emissions) and in field application (giving an estimated 60% reduction). Adjacent to nature areas, shallow injection of manure is required. However, a new law in Denmark specifies that use of a trailing hose/trailing shoe combined with slurry acidification in this manner is also compliant with the requirements.

176. **Addition of superphosphate and phosphogypsum.** According to many years of practice in the Russian Federation, an effective way to achieve a substantial reduction in losses of NH_3 from the storage and spreading of liquid manure and dung is the addition of superphosphate and phosphogypsum. Manure and phosphogypsum are used in a ratio of 20 to 1 depending on the retention periods, which reduces the emission of NH_3 by 60%. The presence of phosphogypsum in composts based on manure and dung can increase the effectiveness of their use by half, especially when used for cruciferae crops (Novikov and others 1989; Eskov and others, 2001). The main regulatory factor for use of composts with phosphogypsum in an intensive mode is a dangerous excess accumulation of associated fluoride and strontium contaminants in soil. In the Russian Federation this practice represents the agricultural utilization of industrial phosphogypsum wastes arising from sulphuric acid manufacture. Care should be taken in nutrient management planning to match crop recommendations for both N and P, avoiding oversupply of P.

Category 3 techniques

177. **Other additives.** Salts of calcium (Ca) and magnesium (Mg), acidic compounds (e.g., $FeCl_3$, $Ca(NO_3)_2$) and super-phosphate have been shown to lower NH_3 emission, but (with the exception outlined in paragraph 169) the quantities required are generally too large to be practically feasible. Absorbent materials such as peat or zeolites have also been used. There is also a range of commercially available additives, but in general these have not been independently tested.

Chapter

8

Fertilizer application

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A. Urea-based fertilizers

178. Ammonia emission from fertilizer applications are dependent on fertilizer type, weather and soil conditions. Emissions from urea-based fertilizers are much greater than from other fertilizer types because rapid hydrolysis of urea will cause a localized rise in pH. Rapid hydrolysis of urea fertilizers often occurs in soils with a lot of urease enzyme due to an abundance of crop residue. Emissions from anhydrous NH_3 may be significant when the injection in the soil is poor and the soil is not well covered following injection; success depends on having the right soil and soil moisture to allow the furrow to close well. Emissions from ammonium sulphate and di-ammonium phosphate are greater following application of these fertilizer types to calcareous (high-pH) soils. Emission reduction techniques are therefore focused on applications of urea-based fertilizers to all soil types and of ammonium sulphate and di-ammonium phosphate applications to calcareous soils. Emission reduction techniques rely on either slowing the hydrolysis of urea to ammonium carbonate, or encouraging the rapid transfer of the fertilizer into the soil (Sommer, Schjoerring and Denmead, 2004).

179. The use of methods to reduce NH_3 emissions from urea-based compounds makes an important contribution to overall NH_3 emission reductions in agriculture. In particular, it should be noted that NH_3 emissions from urea-based fertilizers (typically 5%–40% N loss as NH_3) are much larger than those based on ammonium nitrate (typically 0.5%–5% N loss as NH_3). Although ammonium nitrate is the main form of N fertilizer used in Europe, there remains an ongoing risk that its use might be restricted or prohibited in certain countries for security and/or safety considerations in the future. Already due to security reasons and higher costs, ammonium nitrate has been largely replaced by urea forms throughout North America. Since the measures to reduce NH_3 emissions from urea-based fertilizers remain limited for certain crops, especially for perennial crops, such a change would be expected to significantly increase regional NH_3 emissions.

180. If applied at agronomically sensible rates and times, improved crop N uptake will be the main benefit of mitigating NH_3 emissions, with minimal increases via the other loss pathways (e.g., nitrate leaching, denitrification). In addition, by reducing NH_3 emissions, a similar reduction in indirect N losses is expected (e.g., by reduced leaching and denitrification from forest soils). Considering the whole system (agricultural land, non-agricultural land and transfers by atmospheric dispersion), these measures are not generally expected to increase overall nitrate leaching or nitrous oxide loss. The measures focus on retaining N in the farming system, thereby maximizing productivity (see also section III).

181. *Reference technique*: The reference application technique is surface broadcast application of the N fertilizer. The effectiveness, limitations and cost of the low-emission application techniques are summarized in table 15.

Category 1 techniques

182. Category 1 techniques for urea-based fertilizers include: urease inhibitors, slow-release coatings, soil injection, rapid soil incorporation and irrigation immediately following application. Of these, soil

injection, rapid soil incorporation and irrigation immediately following application would also apply to ammonium sulphate (and di-ammonium phosphate) applications to calcareous soils.

183. **Urease inhibitors** delay the conversion of urea to ammonium carbonate by directly inhibiting the action of the enzyme urease. This delayed/slower hydrolysis is associated with a much smaller increase in pH around the urea prill and, consequently, a significantly lower NH_3 emission (Chadwick and others, 2005; Watson and others, 1994). The delay to the onset of hydrolysis also increases the opportunity for the urea to be washed into the soil matrix, further reducing the potential for NH_3 emissions. Approved urease inhibitors have been listed by the European Union.[13]

184. **Polymer coated urea granules** provide a slow-release fertilizer that may reduce NH_3 emissions (e.g., Rochette and others, 2009), the extent of which will depend on the nature of the polymer coating and whether used with surface fertilizer application or combined with urea injection.

185. **Incorporation of fertilizer into the soil** either by direct closed-slot injection or by cultivation can be an effective reduction technique (Sommer, Schjoerring and Denmead, 2004). For urea prills, combining injection or incorporation with slow-release coatings may allow for a single fertilizer application prior to crop establishment, negating the need for surface application at a later date. Depth of injection and soil texture will influence reduction efficiency. Mixing of the fertilizer with the soil through cultivation may be a less efficient reduction measure than injection to the same depth because a part of the mixed-in fertilizer will be close to the surface. For short-season crops, the seasonal supply of N can be provided by injection of urea in the seeding operation, saving time and money for the farmer. This has been widely adopted by farmers in western Canada.

186. **Irrigation with at least 5 mm water** immediately following fertilizer application has been shown to reduce NH_3 emissions by up to 70% (O. Oenema and Velthof, 1993; Sanz-Cobeña, 2010). Water should not be applied to wet soils beyond field capacity. This is only considered a category 1 technique where there is a water need for irrigation, as the method may otherwise increase the risk of nitrate leaching.

187. **Switching from urea to ammonium nitrate** fertilizer is a rather easy way to reduce NH_3 emissions, with an effectiveness of around 90%. A possible negative side effect is the potential increase in N_2O, especially when the ammonium-nitrate (NH_4NO_3)-based fertilizers are applied to moist or wet soils. The cost of this measure is simply the price differential between the two fertilizer types and the amounts of fertilizer N needed for optimum N fertilization. The gross cost of the NH_3 nitrate fertilizer is higher that urea-based fertilizers, depending on market conditions (range 10%–30%). However, the net cost may negligible or there may be a net gain, because of the lower N losses.

188. **Potential cost implications.** The increased cost of implementing these techniques will be offset to some extent (or provide a net benefit) by savings on fertilizer use to achieve the same yield as for the reference method, or an increased yield from the same rate of fertilizer application.

189. **Impact on N cycle.** If applied in an agronomically sensible way with regard to rates, times and placement, improved crop N uptake will be the main benefit of mitigating NH_3 emissions, with minimal increases via the other loss pathways (e.g., nitrate leaching, denitrification). In addition, by reducing NH_3 emissions, a similar reduction in indirect N losses is expected (e.g., by reduced leaching and denitrification from forest soils). Considering the whole system (agricultural land, non-agricultural land and transfers by atmospheric dispersion), these measures are not generally expected to increase overall nitrate leaching or nitrous oxide loss. The measures focus on retaining N in the farming system, thereby maximizing productivity.

Category 2 techniques

190. **ATMS**. ATMS represents a verified system to exploit the variation in NH_3 emission potential based on environmental conditions, so as to use management of application timing to reduce overall emissions. Fertilizer applications under cooler conditions and prior to rainfall (although bearing in mind the need to avoid the associated risk of run-off to water bodies) are associated with lower NH_3 emissions. If it is to be

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[13] Commission Regulation (EC) No. 1107/2008 of 7 November 2008 amending Regulation (EC) No. 2003/2003 of the European Parliament and of the Council relating to fertilisers for the purposes of adapting Annexes I and IV thereto to technical progress. Available from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008R1107:EN:NOT (accessed on 29 May 2013)

used, this strategy has to be associated with verification of the reference conditions and of the achieved reductions in emissions.

191. **Mixing urea with ammonium sulphate.** Co-granulation of urea and ammonium sulphate may reduce NH_3 emissions compared with urea alone on certain soil types (O. Oenema and Velthof, 1993). Further studies are required across more soil types before recommendations can be made.

Table 15
Mitigation options (category 1) for reducing ammonia emissions from urea-based fertilizers

Abatement measure	*Fertilizer type*	*Emission reduction (%)*	*Factors affecting emission reduction*	*Applicability*	*Cost (€/kg NH_3 abated /year)*
Surface broadcast	Urea-based	Reference			
Urease inhibitor	Urea-based	70 for solid urea, 40 for liquid urea ammonium nitrate		All	-0.5–2.0
Slow-release fertilizer (polymer coatings)	Urea-based	~30	Polymer coating type and integrity; fertilizer application technique (surface or injected)	All	-0.5–2.0
Closed-slot injection	Urea-based and anhydrous ammonia fertilizers	80–90	Depth of placement; soil texture; closure of slot (improperly closed slots may lead to high emissions due to high concentration of urea in the slot, increasing pH)	Tilled or reduced-till land prior to seeding or during the seeding operation or during the mechanical weed control operation after emergence	-0.5–1.0
Incorporation	Urea-based fertilizers	50–80	Delay after fertilizer application; depth of mixing; soil texture	Tilled land prior to crop establishment	-0.5–2.0
Irrigation	All	40–70	Irrigation timing and volume (immediate with ~10mm is most effective); soil humidity; soil texture	Where crop irrigation is commonly practiced	-0.5–1.0
Substitution with ammonium nitrate	Urea-based and anhydrous ammonia fertilizers	Up to 90	Under conditions where urea based fertilizers would have emissions of at least 40%.	All, especially where only surface application of fertilizer and no irrigation is possible	-0.5–1.0

Note: Local costs/benefits will vary, though trials have shown that the financial benefit of increased crop productivity can more than outweigh the costs of the technique for some abatement measures.

Category 3 techniques

192. *Band incorporation of urea.* This technique is not recommended on soils with high urease activity (e.g., with crop residue) and poor ability to adsorb urea, as it can be associated with increased NH_3 emissions in comparison with the reference technique (e.g., Rochette and others, 2009).

B. Ammonium sulphate-, phosphate- and nitrate-based fertilizers

193. *Reference technique:* The reference application technique is the surface application of ammonium sulphate and ammonium phosphate fertilizers.

Category 1 techniques

194. Several of the techniques described above for urea can also be used to reduce NH_3 emissions from ammonium sulphate- and ammonium phosphate-based fertilizers. The highest risks occur when these fertilizers are applied on calcareous or other high-pH soils. Category 1 techniques for ammonium sulphate- and ammonium phosphate-based fertilizers include: incorporation, injection, immediate irrigation and slow-release fertilizers with polymer coatings on high-pH soils (subject to the result of trials).

Category 2 techniques

195. Emissions from non-urea fertilizers such as ammonium nitrate and calcium ammonium nitrate are small, but may occur partly as a result of direct fertilizer emission and partly from indirect emission resulting from plants as a consequence of fertilization. Grass cutting also contributes to the NH_3 emissions, with emissions arising from the re-growing sward as a consequence of cutting-induced N mobilization in the vegetation. Fertilizing grassland within the first few days after cutting provides surplus N resulting in a larger emission from the combined effects of cutting and fertilization. Delaying N fertilizer application following cutting allows the grass to recover, thereby reducing NH_3 emissions. Model analysis found that a two-week delay in N fertilization reduced total (net annual) NH_3 emissions from cut and fertilized grassland by 15 per cent. Similar effects may be achieved with different timing depending on regional conditions. However, this practice will reduce herbage yield. Given the interactions with weather and the need for further work to identify the optimum delay in relation to different management systems, this is classed as a category 2 technique. The approach may be integrated into ATMSs.

Chapter

9

Other measures related to agricultural nitrogen

S. Bittman & M.A. Sutton

A. Grazing

196. Urine excreted by grazing animals often infiltrates into the soil before substantial NH_3 emissions can occur. Therefore, NH_3 emissions per animal are less for grazing animals than for those housed where the excreta is collected, stored and applied to land. The emission reduction achieved by increasing the proportion of the year spent grazing will depend, inter alia, on the baseline (emission of ungrazed animals), the time the animals are grazed and the N-fertilizer level of the pasture. The potential for increasing grazing is sometimes limited by land availability, soil type, topography, farm size and structure (distances), climatic conditions, economic considerations, etc. It should be noted that additional grazing of animals may increase other forms of N emission (e.g., N_2O, NO_3). However, given the clear and well quantified effect on NH_3 emissions, this can be classed as a category 1 technique (in relation to modification of the periods when animals are housed or grazed for 24 hours a day). The abatement efficiency may be considered as the relative total NH_3 emissions from grazing versus housed systems (see also paras. 40 and 52).

197. The effect of changing the period of partial housing (e.g., grazed during daytime only) is less certain and is rated as a category 2 technique. Changing from a fully housed period to grazing for part of the day is less effective in reducing NH_3 emissions than switching to complete (24-hour) grazing, since buildings and stores remain dirty and continue to emit NH_3 (see also paras. 40 and 52).

B. Manure treatment

198. Research on various options for reducing NH_3 emissions by manure treatment have been investigated. Some potentially promising options are:

(a) *Composting of solid manure or slurry with added solids*: experimental results are very variable and often show increased NH_3 emissions; for this reason, systems for composting of manure should consider the inclusion of additional methods to reduce NH_3 emissions from this source, such as covers and air scrubbing systems;

(b) *Controlled denitrification processes in the slurry*: pilot storage plants show that it might be possible to reduce NH_3 emissions by transforming ammonium to N_2 gas by controlled denitrification (alternating aerobic and anaerobic conditions). To achieve this, a special reactor is necessary. The efficiency and the reliability of the system and its impact on other emissions need further investigation;

(c) *Manure separation to remove P or to provide bedding*: Emissions from these systems need to be investigated.

199. The efficiency of manure treatment options should generally be investigated under country- or farm-specific conditions. Apart from NH_3 emissions, other emissions, nutrient fluxes and the applicability of the

system under farm conditions should be assessed. Due to the mentioned uncertainties, these measures generally have to be grouped in categories 2 or 3. An exception is the use of air scrubbing systems for manure composting facilities (category 1), which are well tested, but have significant costs.

C. Non-agricultural manure use

200. If manure is used outside of agriculture, agricultural emissions may be reduced. Examples of such uses already common in some countries are the incineration of poultry manure and the use of horse and poultry manure in the mushroom industry. The emission reduction achieved depends on how fast the manure is taken away from the farm and how it is treated. An overall reduction of the emissions will only be achieved if the use of the manure itself does not generate large emissions (including other emissions than NH_3). For example, the use of manure in horticulture or the export of manure to other countries will not reduce overall emissions. There are also other environmental aspects to be considered, for example, poultry litter incineration is a renewable source of energy, but not all the nutrients in the litter will be recycled within agriculture.

Chapter

10

Non-agricultural stationary and mobile sources

S. Bittman, M. Dedina, O. Oenema & M.A. Sutton

201. There are many non-agricultural sources of NH_3, including motor vehicles, waste disposal, residential solid-fuel combustion, and various industries, of which fertilizer production is likely to be the most significant across Europe. There is also a small, but collectively significant, group of natural sources, including, for example, human breath and sweat and emissions from wild animals (Sutton and others, 2000). The ECE protocols for reporting emissions do not currently distinguish between natural and anthropogenic sources in the same way that they do for volatile organic compounds (VOCs).

202. A common factor across many of these sectors is that NH_3 emissions have previously been ignored. This is most notable with respect to transport, as shown below. A first recommendation for reducing NH_3 emissions from non-agricultural sources is therefore to ensure that NH_3 is considered when assessing the performance of industry and other sources. Where NH_3 emissions are found to arise, or are likely to increase through some technical development, it will be appropriate for operators and designers to consider ways in which systems may be optimized to avoid or minimize emissions.

A. General techniques

203. **Venturi scrubbers** are suitable for large gas flows bearing large concentrations of NH_3. Abatement costs are in the region of €3,500/ton, excluding effluent treatment costs. As in all cases discussed in this section, the precise cost-effectiveness will vary according to the size of the installation, NH_3 concentrations and other factors.

204. **Dilute acid scrubbers**, consisting of a tower randomly packed with tiles through which slightly acidic water is circulated, are suitable for dealing with flows of between 50 and 500 tons per year. Barriers to the technology include its limited suitability for large volume gas flows, potentially high treatment costs for effluents and safety hazards linked to storage of sulphuric acid. Reported costs show great variability, from €180 to €26,000/ton NH_3. Variation is again largely a function of installation size and NH_3 flow rate.

205. Regenerative thermal oxidation uses a supplementary fuel (typically natural gas) to burn NH_3 present in a gas stream, with costs reported in the range of €1,900 to €9,100/ton of NH_3.

206. Biofiltration is suitable for low-volume gas flows with low concentrations of NH_3, abating emissions of around 1 ton per year. It is the least-cost system for small sources. Abatement costs of €1,400 to €4,300/ton have been reported, depending on the sector.

207. Abatement efficiencies of the techniques described in this section are typically around 90 per cent.

B. Techniques suited to selected sectors

208. **Emissions of NH_3 from road transport** increased greatly in the 1990s as a result of the introduction of catalyst-equipped vehicles (an estimate for the United Kingdom of Great Britain and Northern

Ireland shows a factor of 14 increase over this period). The problem is largely being resolved through the introduction of better fuel management systems, moving from carburettor-control to computerized systems that exercise much tighter control over the ratio of air to fuel. Moves to reduce the sulphur content of fuels, some methods for nitrogen oxides (NO_x) control from diesel-engine vehicles, and the use of some alternative fuels may start to increase emissions. Despite the consequences for NH_3 of all of these actions, it has not been considered as a priority pollutant by either vehicle manufacturers or by regulators. It is therefore important that for this and other sectors, account be taken of the impact of technological changes on NH_3 emissions. By doing so, actions can be undertaken to avoid or minimize emissions during the design phase, where potential problems are identified.

209. **Ammonia slippage in stationary catalytic reduction facilities.** For a number of sectors, the most significant source of NH_3 release may be linked to the slippage of NH_3 from NO_x abatement facilities. Two types of technique are available, scrubbing NH_3 slip from the flue gases, which can reduce emissions from about 40 mg/m^3 by around 90 per cent, and more effective control of NO_x control equipment. The potential for NH_3 emissions from this source will need to be considered carefully as NO_x controls increase through wider adoption of BAT.

210. **Non-evaporative cooling systems** are applicable to the sugar beet industry. These systems are more than 95 per cent effective in reducing emissions. Costs are estimated at €3,500/ton NH_3 abated.

211. **Emissions from domestic combustion** can be reduced using a wide variety of techniques, ranging from the adoption of energy-efficiency measures, to the use of better quality fuels, to optimization of burning equipment. There are significant barriers to the introduction of some of these options, ranging from the technical (e.g., lack of natural gas infrastructure) to the aesthetic (e.g., people liking the appearance of an open wood-burning fire).

212. **Capping landfill sites.** Waste disposal by landfilling or composting has the potential to generate significant amounts of NH_3. Actions to control methane emissions from landfill, such as capping sites and flaring or utilizing landfill gas, are also effective in controlling NH_3.

213. **Biofiltration** (see above) is effectively used at a number of centralized composting facilities, often primarily for control of odours, rather than NH_3 specifically. A more general technique, applicable to home composting as well as to larger facilities, is to control the ratio of carbon to nitrogen, aiming for an optimum of 30:1 by weight.

214. **Horses.** Assessment needs to be undertaken of the extent to which emissions from horses are included in the agricultural and non-agricultural inventories. Many horses are kept outside of farms and so may be excluded from agricultural inventories. The most effective approach for reducing emissions from these sources is good housekeeping in stables, with provision of sufficient straw to soak up urine, and daily mucking out. More sophisticated measures for controlling emissions, such as the use of slurry tanks are unlikely to be implemented at small stables, but are described elsewhere in this document.

C. Production of inorganic nitrogen fertilizers, urea and ammonia

215. The most important industrial sources of NH_3 emissions are mixed fertilizer plants producing ammonium phosphate, nitrophosphates, potash and compound fertilizers, and nitrogenous fertilizer plants manufacturing, inter alia, urea and NH_3. Ammonia phosphate production generates the most NH_3 emissions from the sector. Ammonia in uncontrolled atmospheric emissions from this source has been reported to range from 0.1 to 7.8 kg N/ton of product.

216. Nitrogenous fertilizer manufacture covers factories producing NH_3, urea, ammonium sulphate, ammonium nitrate and/or ammonium sulphate nitrate. The nitric acid used in the process is usually produced on site as well. Ammonia emissions are particularly likely to occur when nitric acid is neutralized with anhydrous NH_3. They can be controlled by wet scrubbing to concentrations of 35 mg NH_3/m^3 or lower. Emission factors for properly operated facilities are reported to be in the range of 0.25–0.5 kg NH_3/ton of product.

217. Additional pollution control techniques beyond scrubbers, cyclones and baghouses that are an integral part of the plant design and operations are generally not required for mixed fertilizer plants. In general, an NH_3 emission limit value of 50 mg NH_3-N/m^3 may be achieved through maximizing product recovery and minimizing atmospheric emissions by appropriate maintenance and operation of control equipment.

218. In a well-operated plant, the manufacture of NPK fertilizers by the nitrophosphate route or mixed acid routes will result in the emission of 0.3 kg/ton NPK produced and 0.01 kg/ton NPK produced (as N). However, the emission factors can vary widely depending on the grade of fertilizer produced.

219. Ammonia emissions from urea production are reported as recovery absorption vent (0.1–0.5 kg NH_3/ton of product), concentration absorption vent (0.1–0.2 kg NH_3/ton of product), urea prilling (0.5–2.2 kg NH_3/ton of product) and granulation (0.2-–0.7 kg NH_3/ton of product). The prill tower is a source of urea dust (0.5–2.2 kg NH_3/ton of product), as is the granulator (0.1–0.5 kg/ton of product as urea dust).

220. In urea plants, wet scrubbers or fabric filters are used to control fugitive emissions from prilling towers and bagging operations. This control equipment is similar to that in mixed fertilizer factories, and is an integral part of the operations to retain product. If properly operated, new urea plants can achieve emission limit values of particular matter below 0.5 kg/ton of product for both urea and NH_3.

Annex I

Supplementary information:
Nitrogen management

O. Oenema, S. Bittman, M. Dedina, C.M. Howard & M.A. Sutton

1. Management can be defined as a coherent set of activities to achieve objectives. This definition applies to all sectors of the economy, including agriculture. Nitrogen management can be defined as “a coherent set of activities related to N use in agriculture to achieve agronomic and environmental/ecological objectives” (O. Oenema and Pietrzak, 2002). The agronomic objectives relate to crop yield and quality, and animal performance in the context of animal welfare. The environmental/ecological objectives relate to N losses from agriculture. Taking account of the whole N cycle emphasizes the need to consider all aspects of N cycling, also in NH_3 emissions abatement, to circumvent pollution swapping.

2. Nitrogen is a constituent of all plant and animal proteins (and enzymes) and it is involved in photosynthesis, eutrophication, acidification and various oxidation-reduction processes. Through these processes, N changes in form (compounds), reactivity and mobility. Main mobile forms are the gaseous forms N_2, NH_3, nitrogen oxides (NO and NO_2), and N_2O, and the water soluble forms nitrate (NO_3^-), ammonium (NH_4^+) and dissolved organically bound N (DON). In organic matter, most N is in the form of amides, linked to organic carbon ($R\text{-}NH_2$). Because of the mobility in both air and water, reactive N is also called “double mobile”.

3. The N cycle is strongly linked with the carbon cycle and with other nutrient cycles. Hence, managing N may affect the cycling of carbon and the net release of CO_2 into the atmosphere and the sequestration of carbon in soils. Generally, a leaky system for N is also a leaky system for carbon, and vice versa. This highlights the importance of considering N management from a whole-farm perspective.

4. Depending on the type of farming systems, N management at farm level involves a series of management activities in an integrated way, including:

   (a) Fertilization of crops;

   (b) Crop growth, harvest and residue management;

   (c) Growth of catch or cover crops;

   (d) Grassland management;

   (e) Soil cultivation, drainage and irrigation;

   (f) Animal feeding;

   (g) Herd management (including welfare considerations), including animal housing;

   (h) Manure management, including manure storage and application;

   (i) Ammonia emission abatement measures;

   (j) Nitrate leaching and run-off abatement measures;

   (k) N_2O emission abatement measures;

(l) Denitrification abatement measures.

To be able to achieve high crop and animal production with minimal N losses and other unintended environmental consequences, all activities have to be considered in an integrated and balanced way.

5. Nitrogen is essential for plant growth. In crop production, it is often the most limiting nutrient, and therefore must be available in sufficient amount and in a plant-available form in soil to achieve optimum crop yields. Excess and/or untimely N applications are the main source of N losses in the environment, including NH_3 emissions to air. To avoid excess or untimely N applications is one of the best ways to minimize N losses (and other environmental impacts), while not affecting crop and animal production. Guidelines for site-specific best nutrient management practices should be adhered to, including:

(a) Nutrient management planning and recordkeeping, for all essential nutrients;

(b) Calculation of the total N requirement by the crop on the basis of realistic estimates of yield goals, N content in the crop and N uptake efficiency by the crop;

(c) Estimation of the total N supply from indigenous sources, using accredited methods:

  (i) Mineral N in the upper soil layers at planting and in-crop stages (by soil and/or plant tests);

  (ii) Mineralization of residues of the previous crops;

  (iii) Net mineralization of soil organic matter, including the residual effects of livestock manures applied over several years and, on pastures, droppings from grazing animals;

  (iv) Deposition of reactive N from the atmosphere;

  (v) Biological N_2 fixation by leguminous plants;

(d) Computation of the needed N application, taking account of the N requirement of the crop and the supply by indigenous N sources;

(e) Calculation of the amount of nutrients in livestock manure applications that will become available for crop uptake. The application rate of manure will depend on:

  (i) The demands for N, phosphorus and potassium by the crops;

  (ii) The supply of N, phosphorus and potassium by the soil, based on soil tests;

  (iii) The availability of livestock manure;

  (iv) The immediately available N, phosphorus and potassium contents in the manure and;

  (v) The rate of release of slowly available nutrients from the manure, including the residual effects;

(f) Estimation of the needed fertilizer N and other nutrients, taking account of the N requirement of the crop and the supply of N by indigenous sources and livestock manure;

(g) Application of livestock manure and/or N fertilizer shortly before the onset of rapid crop growth, using methods and techniques that prevent NH_3 emissions;

(h) Where appropriate, application of N fertilizer in multiple portions (split dressings) with in-crop testing, where appropriate.

6. Preferred measures for reducing overall NH_3 emissions are those that decrease other unwanted N emissions simultaneously, while maintaining or enhancing agricultural productivity (measures with synergistic effects). Conversely, measures aimed at reducing NH_3 emissions that increase other unwanted emissions (antagonistic effects) should be modified to so that the antagonistic effects are minimized. Such antagonistic effects may include increased CH_4 emissions from ruminants. Similarly, abatement measures should avoid increasing other types of farm pollution (e.g., phosphorus (P) losses, pathogens, soil erosion) or resource use (e.g., fuel), reducing the quality of food (e.g., increased antibiotics, hormones or pesticides) or detrimentally impacting the health and welfare of farm animals (e.g., by limiting barn size or animal densities) (Jarvis and others, 2011).

7. The effectiveness of N management can be evaluated in terms of (a) decreases of Nsurplus; and (b) increases of NUE. NUE indicators provide a measure for the amount of N that is retained in crop or animal products, relative to the amount of N applied or supplied. Nsurplus is an indicator for the N pressure of the farm on the wider environment, also depending on the pathway through which surplus N is lost, either as NH_3 volatilization, N leaching and/or nitrification/denitrification. Management has a large effect on both NUE (Tamminga 1996; Mosier, Syers and Freney, 2004) and Nsurplus.

8. While the ratio of total N output (via products exported from the farm) and total N input (imported into the farm, including via biological N_2 fixation) (mass/mass ratios) is an indicator for the NUE at farm level, the total N input minus the total N output (mass per unit surface area) is an indicator of the Nsurplus (or deficit) at farm level.

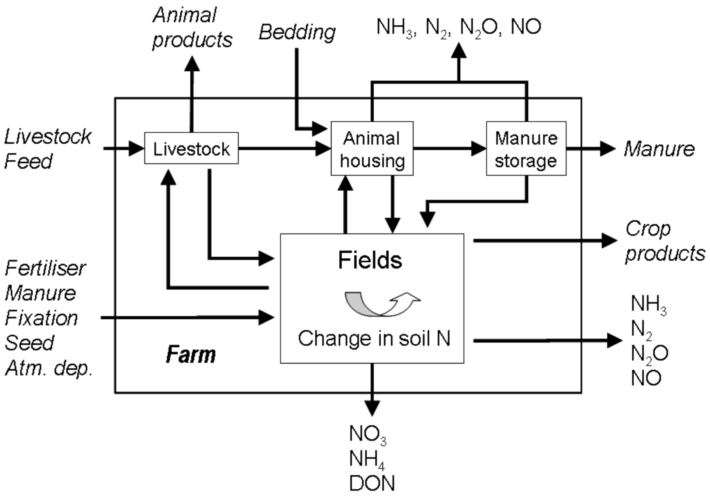
9. Commonly, a distinction is made between N input-output balances and N input-output budgets. Balances and budgets apply similar input items; the main difference is that balances record the N output in harvested/marketable products only, while budgets record the N output via harvested/marketable products and losses from the system. Hence, budgets provide a full record and account of all N flows.

10. There are various procedures for making N input-output balances, including the gross N balance, the soil-surface balance, the farm-gate balance, and the farm balance (e.g., Watson and Atkinson, 1999; Schroder and others, 2003; O. Oenema, Kros and de Vries, 2003; OECD, 2008). Basically, the gross N balance and the soil-surface balance record all N inputs to agricultural land and all N outputs in harvested crop products from agricultural land. However, the balances differ in the way they account for the N in animal manure; the gross N balance includes the total amount of N excreted as an N input item, while the soil-surface balance corrects the amount of N excreted for NH_3 losses from manure in housing systems and manure storage systems. The farm-gate balance and the farm balance records all N inputs and all N outputs of the farm; the farm balance includes N inputs via atmospheric deposition (both reduced and oxidized N compounds) and biological N_2 fixation. Various methods can be applied at the field, farm, regional and country levels; it is important to use standardized formats for making balances and to report on the methodology so as to improve comparability.

11. A farm N budget of a mixed crop-animal production farm is the most complex budget (figure AI.1). The main inputs are mineral/inorganic fertilizer, imported animal manure, fixation of atmospheric N_2 by some (mainly leguminous) crops, deposition from the atmosphere, inputs from irrigation water and livestock feed. Inputs in seed and bedding used for animals are generally minor inputs, although the latter can be significant for some traditional animal husbandry systems. The main outputs are in crop and animal products, and in exported manure. Gaseous losses occur from manure in animal housing, in manure storage and after field application. Other gaseous losses occur from fields; from applied fertilizer, crops, soil and crop residues. Losses to groundwater and surface water occur via leaching or run-off of nitrates, ammonium and DON. Run-off of undissolved organic N may also occur.

Figure AI.1

A farm N budget of a mixed crop-animal production farm

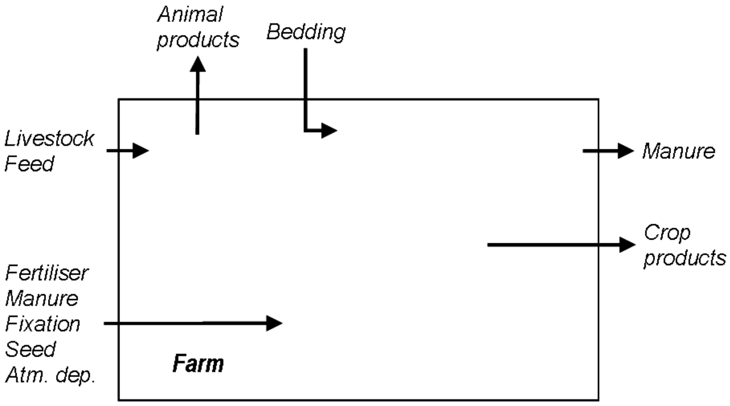


Source: Jarvis and others, 2011.

12. The corresponding components of a farm N balance of a mixed crop-animal production farm are shown in figure AI.2. Evidently, a farm N balance is much simpler than a farm N budget, as N losses to air, groundwater and surface waters are not included in the N balance. A farm N balance of a specialized crop production farm or a specialized animal production farm are much simpler than a farm gate-balance of a mixed crop-animal production farm, because there are less types of N inputs and outputs.

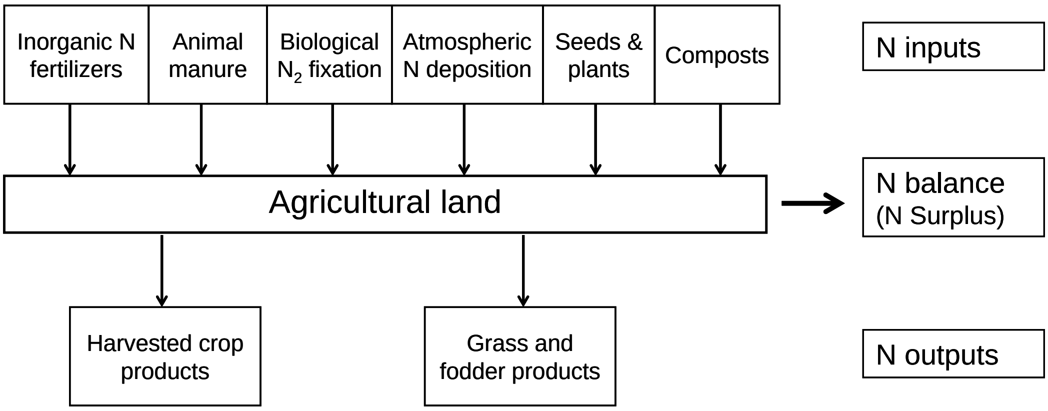
Figure AI.2

Components of a farm N balance of a mixed crop-animal production farm



13. A soil surface N balance of agricultural land is shown in figure AI.3. The main N inputs are mineral/inorganic fertilizer, animal manure, fixation of atmospheric N by some (mainly leguminous) crops and deposition from the atmosphere. Other N inputs may include bio-solids, and organic amendments like compost and mulches. Inputs in seed and composts are generally minor inputs. The main outputs are in harvested crop products, which may be the grain or the whole crop. Note that animal products other than animal manure do not show up in the soil surface balance, as they are not placed onto the soil surface.

Figure AI.3
Components of a soil surface N balance of agricultural land



Source: OECD, 2008.

14. For using N balances and NUE as indicators at farm level, a distinction has to be made between:

(a) Specialized crop production farms;

(b) Mixed crop (feed)-animal production farms;

(c) Specialized animal production farms.

15. Specialized crop production farms have relatively few NH_3 emission sources (possibly imported animal manure, urea and ammonium-based fertilizers, crops and residues). These farms can be subdivided according to crop rotation (e.g., percentage of cereals, pulses, vegetables and root crops). Specialized animal production farms produce only animal products (milk, meat, egg, animal by-products and animal manure) and all these products are exported from the farm. Energy may also be produced through digestion of organic carbon. These farms can be subdivided according to animal categories (e.g., pig, poultry, and cattle). Mixed systems have both crops and animals; the crops produced are usually fed to the animals, while the manure produced by the animals is applied to the cropland. These farms can be subdivided according animal categories (e.g., dairy cattle, beef cattle, pigs, etc.) and livestock density (or feed self-sufficiency).

16. The variation between farms in NUE (output/input ratios) and Nsurpluses (input minus output) is large in practice, due to the differences in management and farming systems (especially as regards the types of crops and animals, the livestock density and the farming system). Indicative ranges can be given for broad categories of farming systems (see table AI.2).

17. Nitrogen balances and N output-input ratios can be made also for compartments within a farm, especially within a mixed farming system. For estimating NUE, three useful compartments or levels can be considered:

(a) Feed N conversion into animal products (feed-NUE or animal-NUE);

(b) Manure and fertilizer N conversion into crops (manure/fertilizer-NUE);

(c) Whole-farm NUE.

18. These NUEs are calculated as the percentage mass of N output per mass of N input:

(a) Feed-NUE = [(N in milk, animals and eggs) / (N in feed and fodder)] x 100%;

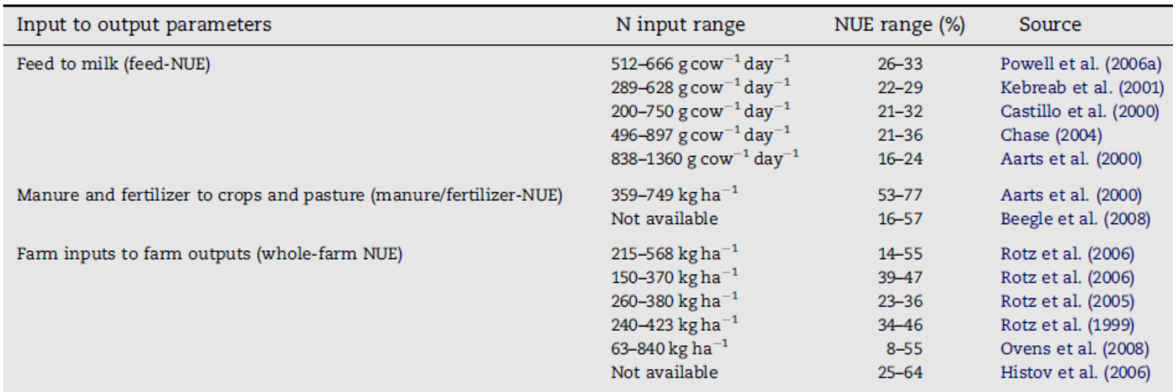
(b) Manure/fertilizer-NUE = [N uptake by crops / N applied as manure/fertilizer] x 100%;

(c) Whole-farm NUE = [Σ(N exported off-farm) / Σ(N imported on to the farm)] x 100%.

Indicative ranges of NUEs for dairy farms are shown below in table AI.1.

Table AI.1

Indicative values for N input and NUE of dairy farms



Input to output parameters	N input range	NUE range (%)	Source
Feed to milk (feed-NUE)	512–666 g cow^{-1} day^{-1}	26–33	Powell et al. (2006a)
	289–628 g cow^{-1} day^{-1}	22–29	Kebreab et al. (2001)
	200–750 g cow^{-1} day^{-1}	21–32	Castillo et al. (2000)
	496–897 g cow^{-1} day^{-1}	21–36	Chase (2004)
	838–1360 g cow^{-1} day^{-1}	16–24	Aarts et al. (2000)
Manure and fertilizer to crops and pasture (manure/fertilizer-NUE)	359–749 kg ha^{-1}	53–77	Aarts et al. (2000)
	Not available	16–57	Beegle et al. (2008)
Farm inputs to farm outputs (whole-farm NUE)	215–568 kg ha^{-1}	14–55	Rotz et al. (2006)
	150–370 kg ha^{-1}	39–47	Rotz et al. (2006)
	260–380 kg ha^{-1}	23–36	Rotz et al. (2005)
	240–423 kg ha^{-1}	34–46	Rotz et al. (1999)
	63–840 kg ha^{-1}	8–55	Ovens et al. (2008)
	Not available	25–64	Histov et al. (2006)

Source: Powell, Rotz and Weaver, 2009.

19. For assessing the feed-NUE or animal-NUE, the amounts of feed plus fodder consumed and the N contents of the feeds plus the fodders have to be known. Also the amounts of N in animal products (protein in milk, meat and eggs) have to be known. Default values can be used for N in milk-protein, eggs and live-weight, carcass-weight and meat for cattle, pigs and poultry.

Table AI.2

Nsurplus and NUE indicators of farming systems, with typical values for specialized crop production farms, specialized animal production farms and mixed farms

Index	*Calculation*	*Interpretation*	*Typical levels*
Nsurplus = sum of all N inputs minus the N outputs that pass the farm gate, expressed in kg/ha/yr	N surplus = Σ (Inputs$_N$) – Σ (outputs$_N$)	Nsurplus depends on the types of farming system, crops and animals, and indigenous N supply, external inputs (via fertilizers and animal feed) management and environment Nsurplus is a measure of the total N loss to the environment N deficit [Σ (Inputs$_N$) < Σ (outputs$_N$] is a measure of soil N depletion For specialized animal farming systems (landless), the Nsurplus can be very large, depending also on the possible N output via manure processing and export	Depends on types of farming systems, crops and animals: Crop: 0–50 kg/ha Mixed: 0–200 kg/ha Animal: 0–1,000 kg/ha
NUE = N use efficiency, i.e., the N output in useful products divided by the total N input	NUE = Σ (outputs$_N$) / Σ (Inputs$_N$)	NUE depends on types of farming system, crops and animals, and indigenous N supply, external inputs (via fertilizers and animal feed) management and environment For specialized animal farming systems (landless), there may be N output via manure processing and export	Depends on types of farming systems, crops and animals: Crop 0.6–1.0 Mixed: 0.5–0.6 Animal 0.2–0.6[a] Animal 0.8–0.95[b]

[a] No manure export.

[b] Landless farms; all manure exported off-farm.

20. For assessing the manure/fertilizer-NUE, it is useful to make a distinction between different N input sources. The “fertilizer N equivalence value” indicates how well N from animal manures, composts and crop residues are used relative to the reference fertilizer (commonly NH_4NO_3-based fertilizers), which is set at 100%. A high value is indicative for a high NUE. The fertilizer N equivalence value depends on the type (solid, slurry or liquid) and origin (cattle, pigs, poultry) of manure and the time frame (year of application versus long-term effects). It also depends on crop type and environmental conditions (soil type, temperature, rainfall). A most decisive factor for a high fertilizer N equivalence value is management, i.e., the time and method of application. Table AI.3 gives ranges of N fertilizer equivalence values for cattle, pig and poultry manure, slurries and liquid manures, as found in literature. Organic N sources usually contain a significant fraction of organically bound N, which becomes available to growing crops only after mineralization. Therefore, a distinction is made between short-term (i.e., during the growing season immediately after application of the organic N source) and long-term fertilizer N equivalence values; the latter being higher than the former. Some organic N sources have only mineral N and easily mineralizable organic N, and as a consequence there is essentially no difference between short-term and long-term values.

Table AI.3

Ranges of short-term and long-term fertilizer N equivalence values (FNEV) of applied animal manures and crop residues, expressed as a percentage of the reference fertilizer, ammonium-nitrate

	Fertilizer N equivalence values (%)	
Nitrogen sources	*Short-term*	*Long-term*
Separated cattle and pig liquid manures	70–100	70–100
Digested cattle and pig slurries	40–60	50–80
Cattle slurries	30–50	50–80
Pig slurries	30–65	50–80
Poultry slurries	30–65	50–80
Solid cattle, pig and poultry manures	20–40	40–60
Composts of cattle, pig and poultry manures	20–40	40–60
Urine and dung from grazing animals	10–20	20–40
Crop residues with more than 2.5% N	10–40	30–50
Crop residues with 1.5%–2.5% N	0–30	20–40
Crop residues with less than 1.5% N	0	0–20

Sources: Berntsen and others, 2007; Bittman and others, 2007; Burton and Turner, 2003; Chadwick and others, 2000; Gutser and others, 2005; Hadas and others, 2002; Hart and others, 1993; Hatch and others, 2004; Janssen, 1984; Jenkinson and Smith, 1988; Kolenbrander and De La Lande Cremer, 1967; Langmeier and others, 2002; MacDonald and others, 1997; Mosier, Syers and Freney, 2004; Nevens and Reheul, 2005; Rufino and others, 2006; Rufino and others, 2007; Schils and Kok, 2003; Schröder and others, 2000; Schröder and Stevens, 2004; Schröder 2005; Schröder, Jansen and Hilhorst, 2005; Schröder, Uenk and Hilhorst, 2007; Sommerfeldt, Chang and Entz, 1988; Sørensen, 2004; Sørensen and Amato, 2002; Sørensen, Weisbjerg and Lund, 2003; Sørensen and Thomsen, 2005; Van der Meer and others, 1987; Velthof and others, 1998.

Notes: The manures are applied with common low-emission application techniques. The short-term fertilizer N equivalence values relate to the fertilizer N equivalence value of timely applications during the year of application. The long-term fertilizer N equivalence values include residual effects and assume repeated annual applications.

21. For whole farms, the Nsurplus and NUE of specialized crop production farms are estimated as follows:

SurplusN = [FertN + ManureN + CompostN + BNF + Atm.N + SeedN] – [CropN] [1]

NUEcrop = [CropN] / [FertN + ManureN + CompostN + BNF + Atm.N + SeedN] [2]

Where,

SurplusN = NSurplus at farm level, kg/ha

NUEcrop = N use efficiency at farm level, mass/mass ratio (dimensionless)

FertN = Amount of fertilizer N fertilizer imported to the farm, kg/ha

ManureN = Amount of manure N imported to the farm, kg/ha

CompostN = Amount of compost N imported to the farm, kg/ha

BNF= Amount of biologically fixed N2 by leguminous crops, kg/ha

Atm.N = Amount of N from atmospheric deposition, kg/ha

SeedN = Amount of N imported via seed and plants, kg/ha

CropN = Net amount of N in harvested crop exported from the farm, including residues, kg/ha.

22. There may be additional N inputs at the farm via, for example, autotrophic N_2 fixation, crop protection means, irrigation water, biosolids or mulches. These inputs are usually small relative to the former and are also difficult to manage. Therefore, these additional N inputs are often disregarded. However, when these inputs are a significant percentage of the total input (> 10%), they should be included in the balance calculations. This may hold for farms on organic soils where the net mineralization of organically bound N may release 20–200 kg of N per ha per year, depending on the trophic status of the peat and drainage conditions.

23. A more accurate expression of the NUE and Nsurplus of specialized crop production farms takes into account the differences in fertilizer N equivalence values of manure, composts and BNF, and is estimated as follows:

NUEcrop = [CropN] / [FertN + (ManureN x FnevM) + (CompostN xFnevC) + (BNF) + Atm.N + SeedN] [7]

Where,

FnevM = fertilizer N equivalence value for manure, kg/kg

FnevC = fertilizer N equivalence value for compost, kg/kg.

24. For specialized landless animal production farms, the Nsurplus and NUE are estimated as follows:

SurplusN = [FeedN] – [AnimalN + ManureN] [3]

NUEanimal = [AnimalN + ManureN] / [FeedN] [4]

Where,

SurplusN = NSurplus at farm level, kg

NUEanimal = N use efficiency at farm level, mass/mass ratio (dimensionless)

FeedN = Net amount of N in animal feed imported to the farm, kg

AnimalN = Net amount of N in animals exported from the farm (i.e., including dead animals and corrected for imported animals), kg

ManureN = Net amount of manure N exported from the farm (including feed residues), kg.

There will be small additional N inputs at the farm via, for example, drinking and cleaning water, litter (bedding material) and medicines, but these inputs are usually small (< 5%) relative to the former, and may be disregarded in this case.

25. For mixed crop- animal production farms, the Nsurplus and NUE are estimated as follows:

SurplusN = [FertN + FeedN + ManureN_i + CompostN + BNF + Atm.N + SeedN] –[AnimalN + CropN + ManureN_e] [5]

NUEmixed = [AnimalN + CropN + ManureN_e] / [FertN + FeedN + ManureN_i + CompostN + BNF + Atm.N + SeedN] [6]

Where,

SurplusN = NSurplus at farm level, kg/ha

FertN = Amount of fertilizer N fertilizer imported to the farm, kg/ha

FeedN = Amount of N in animal feed imported to the farm, kg/ha

$ManureN_i$ = Amount of manure N imported to the farm, kg/ha

CompostN = Amount of compost N imported to the farm, kg/ha

BNF= Amount of biologically fixed N_2 by leguminous crops, kg/ha

Atm.N = Amount of N from atmospheric deposition, kg/ha

SeedN = Amount of N imported via seed and plants, kg/ha

CropN = Amount of N in harvested crop exported from the farm, including residues, kg/ha

AnimalN = Amount of N in animals exported from the farm (i.e., including dead animals and corrected for imported animals), kg

$ManureN_e$ = Amount of manure N exported from the farm, kg/ha.

26. Improvements in N management (and hence decreases in N losses) over time follow from decreases in Nsurpluses and increases in NUE over time. Progress in N management can thus be assessed through the monitoring of the annual Nsurplus and NUE at farm level. To account for annual variations in weather conditions and incidental occasions, it is recommended to calculate five-year averages of Nsurplus and NUE.

27. The relative performance of the N management of farms can be assessed on the basis of comparisons with other farms, model farms or experimental farms. Target values for Nsurpluses and NUE of specialized crop production systems can be based on the performance of best managed (experimental/model) crop production systems in practice, taking soil factors into account.

28. Crops differ in their ability to take up N from soil, due to differences in root length distribution and length of the growing season. Graminae (cereals and grassland) have a high uptake capacity; leafy vegetables (lettuce, spinach) a small uptake capacity. Indicative target values for N surplus and NUE should be specified according to the areal fraction of cereals and grassland on the farm (e.g., in five classes: < 25%; 25%–50%, 50%–75%, 75%–90% and > 90%) (table AI.4).

29. For specialized crop production farms growing cereals on > 90% of the area, and using the input items of equation [7] and the fertilizer N equivalence values (FNEV) from table AI.3, the harvested N roughly equals the total effective N input and NUEcrop may be up to 100%. However, NUEcrop decreases with increasing N input, the impact of pests, or limitation of other nutrients; the challenge is to find the optimum N fertilization level where both crop yield, crop quality and NUE are high and Nsurplus is low. With decreasing relative area of cereals in the crop rotation, target NUE will decrease and Nsurpluses will increase, depending also on the effective N input (table AI.4). The N surplus and NUE also depend on the fate of the crop residue; harvesting and withdrawal of the crop residues increases NUE and decreases Nsurplus, especially in the short term. However, removing crop residues may contribute ultimately to decreasing stocks of soil organic matter and N. Note that NUE and Nsurplus are inversely related (table AI.4). However, this is not always the case; there are possible situations where increasing NUE is associated with slightly increasing Nsurplus.

30. The NUE of specialized animal farms and mixed farms depends in part on the “unavoidable” gaseous N losses from animal manures in housing systems and manure storages due to NH_3 volatilization and nitrification-denitrification processes. Unavoidable N losses are N losses that occur when using BAT. Target values for NUEanimal should be based on the following equation:

TargetNUEanimal = [AnimalN + (ExcretedN – ManureNloss)] / [FeedN] [8]

Where,

TargetNUEanimal = N use efficiency at farm level, mass/mass ratio (dimensionless)

AnimalN = Net amount of N in animals exported from the farm (i.e., including dead animals and corrected for imported animals), kg

FeedN = Net amount of N in animal feed imported to the farm, kg

ExcretedN= Amount of N excreted by animals during confinement, kg

ManureNloss= Unavoidable N losses from animal manure in animals housings and manure storages due to NH_3 volatilization and nitrification-denitrification processes, kg

ExcretedN – ManureNloss = amount of manure N exported from the farm.

Table AI.4

Indicative values for NUE and Nsurpluses of specialized crop production farms at moderate and high N inputs, and as a function of the percentage of cereals in the crop rotation

	Moderate N inputs			*High N inputs*		
		N surpluses			*N surpluses*	
Cereals (%)	*NUE (%)*	*50 kg/ha/yr*	*100 kg/ha/yr*	*NUE (%)*	*150 kg/ha/yr*	*200 kg/ha/yr*
90–100	100	0	0	80	30	40
75–90	95	2.5	5	75	37.5	50
50–75	90	5	10	70	45	60
25–50	80	10	20	60	60	80
< 25	70	15	30	50	75	100

31. ManureNloss values depend on the animal housing system, manure management systems and farm practices. For cattle and pigs housed all year in slurry-based systems with covered manure storages, ManureNloss will be in the range of 5%–20% of manure N excreted during confinement, with the lower value for low-emission housing systems (and tie stalls) and the higher value for houses with partially slatted floors, but depending also on climatic conditions (Amon and others, 2001; Monteny and Erisman, 1998; O. Oenema and others, 2008). When animals are confined only during the winter season, less N will be excreted during confinement and ManureNloss per animal head will be lower. ManureNloss from housing systems with solid manure tend to be higher (20%–40% when housed all year), due to larger nitrification-denitrification losses during manure storage.

32. For poultry, ManureNloss is in the range of 10%–50% of ExcretedN with the lower value for low-emission housing systems and the higher value for deep pits and ground-based litter systems without scrubbing and retaining NH_3 from exhaust air (Groot Koerkamp and Groenestein, 2008).

33. NUE of specialized animal production farms increases with increasing feed N retention and decreasing “unavoidable gaseous N losses” (table AI.5, figure AI.4). Feed N retention depends on animal type, animal productivity and animal feeding. The “unavoidable gaseous N losses” depend on housing system and animal manure management, including low-emission management systems. Hence, NUE of specialized animal production farms is very responsive to gaseous N losses, including NH_3 volatilization losses; it is an integrated N management indicator.

Table AI.5

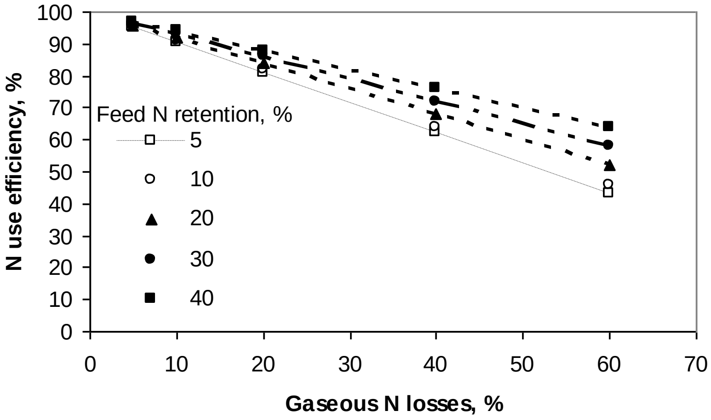
Calculated NUE of specialized animal production farms as a function of the feed N retention percentage and the percentage of “unavoidable N losses” during housing and storage of animal manure (according to equation [8])

	“unavoidable N losses” as% of N excreted				
Feed N retention (%)	**5**	**10**	**20**	**40**	**60**
5	95	91	81	62	43
10	96	91	82	64	46
20	96	92	84	68	52
30	97	93	86	72	58
40	97	94	88	76	64

Note: It is assumed that all animal products, including animal manure, are exported from the farm.

Figure AI.4

Calculated NUE of specialized animal production farms as a function of the feed N retention percentage and the percentage of "unavoidable N losses" during storage of animal manure (according to equation [8])



Note: It is assumed that all animal products, including animal manure, are exported from the farm.

34. Whole farm N balance and NUE are indicators for estimating the pressure of N on the environment and the N resource use efficiency, respectively. Some countries (e.g., Denmark and the Netherlands) use and have used N balances and Nsurplus as integrative regulatory instruments for decreasing N losses to the environment, although there is as yet no experience with using Nsurplus and NUE as specific indicators for abating NH_3 emissions. However, there is solid theoretical and also empirical evidence that increases in NUE are associated with decreases in N losses per unit of produce. Similarly, increases in NUE of animal production systems and mixed production systems are typically associated with decreases in NH_3 losses per unit of produce, as shown, for example, in Denmark (Mikkelsen and others, 2010; Nørregaard Hansen and others, 2008; Anonymous, 2008).

35. Experiences in Denmark and the Netherlands show that most farmers are able to understand the N balance and NUE indicators easily, and are also able to establish N balances and NUE indicators on the basis of bookkeeping records and default values for N contents in various products. However, training and participation in farmers' discussion groups is helpful. Alternatively, N balances and NUE can be calculated by accountants, again on the basis of bookkeeping records and default values for N contents in various products. The annual costs for establishing N balances and NUE indicators is in the range of €200–€500 per farm.

36. Roughly speaking, three strategies/technologies can be distinguished to increase NUE and decrease Nsurplus: (a) increase N outputs through increasing crop and animal yields, while keeping N inputs more or less constant; (b) decrease inputs via N fertilizers and purchased animal feed, while keeping crop and animal yields and N outputs more or less constant; and (c) decrease N losses through N-saving technologies (low-emission techniques, cover crops, better timing of N application, etc.) and thereby save on N inputs, while maintaining N outputs more or less constant. The last mentioned strategy relates in part to the other measures outlined in annex IX to the Gothenburg Protocol; the emphasis is here on cashing in the N saved through its reutilization and through reducing N input concomitantly. The best results will occur when decreased losses are associated with decreased inputs, which will reduce operating costs and the increased outputs necessary for profitability. Hence, the approach to be taken to decrease Nsurplus and increase NUE is farm-specific; there is no uniform approach applicable to all farming systems.

37. There is an abundant amount of information available for increasing NUE and decreasing Nsurplus in crop production systems. Various institutions and fertilizer production companies provide clear guidelines. The International Plant Nutrition Institute provides easy-to-understand and easily accessible guidelines and videos on its website (http://www.ipni.net/4r) for using mineral fertilizers effectively and efficiently. The best management practices for fertilizer is known as the "4R nutrient stewardship concept", i.e., the Right Source, the Right Rate, the Right Time and the Right Place. It can be applied to managing either crop nutrients in general (including organic sources) or fertilizers in particular. This concept can help farmers and the public understand how the right management practices for fertilizer contribute to sustainability goals for agriculture.

In a nutshell, the 4R nutrient stewardship concept involves crop producers and their advisers selecting the right source-rate-time-place combination from practices validated by research conducted by agronomic scientists. Goals for economic, environmental and social progress are set by — and are reflected in performance indicators chosen by — the stakeholders to crop production systems. These are all considered category 1 techniques. Inability to predict weather remains the main impediment to improving crop NUE; other factors include crop pests, poor soils, etc.

38. Increasing NUE and decreasing Nsurplus in mixed crop-animal production systems requires the measures and activities needed for the crop production component (e.g., the 4R concept indicated above), as well as the measures and activities needed in the animal production component (animal feeding, housing and management), and the measures and activities related to manure storage and management.

39. There is not much empirical information about the economic cost of increasing NUE and decreasing Nsurplus direct economic costs. Estimating the direct economic cost is also not easy; it requires proper definitions about the activities that are included in “N management, taking account of the whole N cycle”. Also, a distinction should be made between direct costs and indirect costs. Direct costs relate to the activities needed to increase NUE and decrease Nsurplus, e.g., selection of high-yielding crop and animal varieties and improved tuning of N supply to N demand. These costs are estimated to range between -€1 and +€1 euro per kg N saved. Indirect costs relate to better education of farmers, increased data and information availability through sampling and analysis and through keeping records. The indirect costs are higher than the direct costs, though part of these costs will be returned in terms of higher yields and quality.

Annex
II

Supplementary information:
Livestock feeding strategies

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A. General considerations

1. In practice, protein levels in animal feed are often higher than actually required. Safety margins in the protein content of the diet are used to account for: (a) suboptimal amino acid ratios; (b) variations in requirements between animals with different genotypes; (c) variations in requirements caused by differences in age or production stadiums; and (d) variations in the actual content and digestibility of essential amino acids in the diet. The protein content of the diet and the resulting N excretion can be reduced by matching the protein/amino acids content of the diet as closely as possible to the animal's requirements.

2. The fraction of feed intake not digested, absorbed and retained by the animal is excreted via dung and urine. The excess N in the feed is excreted in the form of protein (organically bound N), urea, uric acid and ammonium. The partitioning of N over these compounds together with the pH of the dung and urine affects the potential for NH_3 loss.

3. There is large variation in the composition of dung and urine from dairy cattle, finishing pigs and chickens, due to variations in animal feeding. Table AII.1 provides ranges of values observed in literature (Canh and others, 1998a, 1998b; Bussink and O. Oenema, 1998; Whitehead, 2000).

Table AII.1

Ranges of N components in dung and urine of some animal species

Animal category	*Dry matter (g per kg)*	*Total N (g per kg dung/urine)*	*Urea-N (% of total N)*	*Uric acid-N (% of total N)*	*Protein-N (% of total N)*	*Ammonium-N (% of total N)*
Dairy Cattle Dung	100–175	10–17	0	0	90–95	1–4
Urine	30–40	4–10	60–95	0–2	0	1
Finishing pigs						
Dung	200–340	8–10	0	—	86–92	8–14
Urine	30–36	4–7	70–90	—	10–20	2–10
Chicken	200–300	10–20	5–8	35–50	30–50	6–8

4. Since the losses of NH_3 are linked to the ammonium, urea and uric acid contents of the urine and dung, the main options to influence the NH_3 emissions potential by livestock feeding are by (figure AII.1):

(a) Lowering the ammonium, urea and uric acid contents of the urine and dung, through:

(i) Lowering the CP intake;

(ii) Increasing the non-starch polysaccharides intake (which shifts the N excretion from urea/uric acid in urine to protein in dung);

(b) Lowering pH of manure by:

(i) Lowering the pH of dung;

(ii) Lowering the pH of urine;

(c) Lowering the urease activity, and hence the ammonium concentrations in manure.

5. The ammonium content of manure (dung plus urine), following the hydrolysis of urea and the anaerobic digestion of protein in manure, can be calculated as follows (Aarnink, van Ouwerkerk and Verstegen, 1992):

$$[NH_4^+] = (dc*P_f - P_r + adc*(1-dc)*P_f) / (M_m)$$

Where:

dc = apparent digestibility coefficient of protein

P_f = protein in feed

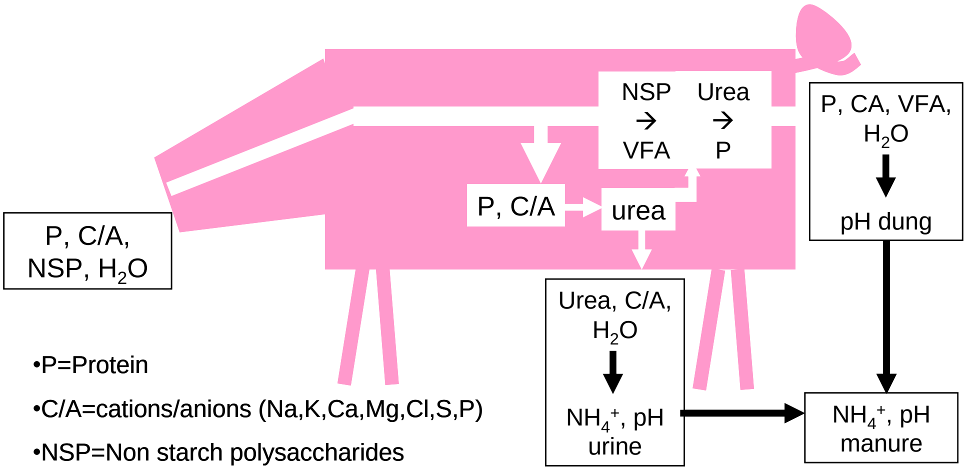
P_r = protein retention

adc = anaerobic digestion coefficient for protein in manure

M_m = mass of manure.

Figure AII.1

Schematic view of the main factors of the animal ration (protein content, cation-to-anion ratio and the content of non-starch polysaccharides) influencing the urea and ammonium contents and pH of the urine and dung excreted by animals



Source: Aarnink and Verstegen, 2007.

6. The pH of urine and manure can be estimated by making a complete cation-to-anion balance. The concentration of ammonium and carbonate also has to be included in this estimate.

7. Livestock feeding strategies can influence the pH of dung and urine. The pH of dung can be lowered by increasing the fermentation in the large intestine. This increases the volatile fatty acids (VFA) content of the dung and causes a lower pH. The pH of urine can be lowered by lowering the electrolyte balance (Na + K – Cl) of the diet (Patience, Austic and Boyd, 1987). Furthermore, the pH of urine can be lowered by adding acidifying components to the diet, e.g., calcium sulphate ($CaSO_4$), Ca-benzoate and benzoic acid. A low pH of the dung and urine excreted also results in a low pH of the slurry/manure during storage even after a certain storage period. This pH effect can significantly reduce NH_3 emissions from slurries during storage and also following application. These effects have been proven especially for pigs (Aarnink and Verstegen, 2007; Canh and others, 1998a, 1998c, 1998d and 1998e).

8. Depending on enzyme activity, urea and uric acid are hydrolyzed into ammonium usually within a few hours to days. The mineralization of organic N (apparent undigested protein) in dung is a slow process. At a temperature of 18°C it takes 70 days before 43% of the organic N in pig manure is mineralized to NH_3 (Spoelstra, 1979). Therefore, by shifting N excretion in cattle and pigs from urine to dung, the N excretion via protein (organically bound N) is increased and the N excretion via urea, uric acid and ammonium is decreased. As a result, NH_3 emissions from the urine are reduced (while NH_3 emissions from dung are not increased).

9. Two indicators are key to indicate the efficiency of the conversion of feed into animal product. They are defined as follows:

(a) The CP requirement (often estimated as the N content multiplied by 6.25) as a proportion of the dietary DM. This depends on animal species, type of production, digestibility of the dietary DM and the quality (amino acid ratio) in the CP. Information on this indicator for concentrate feeds is usually available from the feed company. For forages, notably grazed forages, this may be more difficult, but the sward surface height (SSH) may be a helpful tool; the higher the SSH, the lower the protein content. However, with an increase of SSH, the digestibility of the herbage may decrease;

(b) Efficiency of N utilization (NUE = AY_N/F_N), where AY_N is the mass of N in animal products (in kg), and F_N is the mass of N in the feed used (kg). This indicator requires information on the N content of animal products and animal feeds. Such figures have been extensively tabulated in recent years.

10. Production of animal products (milk, meat, eggs) is not possible without first meeting the nutrient requirements to maintain the animals. Dietary protein levels required for maintenance are much lower than those needed for the synthesis of animal products. Hence, optimal levels of CP/DM vary with the proportion of ingested nutrients that is required for maintenance. This proportion is highest in slow-growing animals, like replacement animals in cattle, and lowest in rapidly growing animals such as broilers.

B. Feeding strategies for ruminants (especially dairy and beef cattle)

11. Ultimately, the NUE in whole-dairy production systems is limited by the biological potential of cows to transform feed N into milk and of crops and pasture to convert applied manure N and fertilizer N into grain, forage and other agronomic products. However, the disparity between actual NUE achieved by producers and the theoretical NUE indicates that substantial improvements in NUE can be made on many commercial dairy farms (e.g., Van Vuuren and Meijs, 1987). Although dairy producers can do little about the biological limitations of N use, practices such as appropriate stocking rates, manure N crediting and following recommendations to avoid wastage can substantially enhance NUE, farm profits and the environmental outcomes of dairy production (Powell, Rotz and Weaver, 2009).

12. Lowering CP of ruminant diets is an effective and category 1 strategy for decreasing NH_3 loss. The following guidelines hold (table AII.2):

(a) The average CP content of diets for dairy cattle should not exceed 150–160 g/kg DM (Broderick, 2003; Swensson, 2003). For beef cattle older than 6 months this could be further reduced to 120 g/kg DM;

(b) Phase feeding can be applied in such a way that the CP content of dairy diets is gradually decreased from 160 g/kg DM just before parturition and in early lactation to below 140 g/kg DM in late lactation and the main part of the dry period;

(c) Phase feeding can also be applied in beef cattle in such a way that the CP content of the diets is gradually decreased from 160 g/kg DM to 120 g/kg DM over time.

Table AII.2
Indicative target levels for CP content, in gram per kg of the dry mass of the ration, and resulting NUE, in mass fractions (kg/kg) for cattle

Cattle species	*CP (g/kg)*	*NUE (kg/kg)*
Milk + maintenance, early lactation	150–160	0.30
Milk + maintenance, late lactation	120–140	0.25
Replacement	130–150	0.10
Veal	170–190	0.45
Cattle < 3 months	150–160	0.30
Cattle 3–18 months	130–150	0.15
Cattle > 18 months	120	0.05

13. In many parts of the world, cattle production is land-based or partly land-based. In such systems, protein-rich grass and grass products form a significant proportion of the diet, and the target values for CP noted in table AII.2 may be difficult to achieve, given the high CP content of grass from managed grasslands. The CP content of fresh grass in the grazing stage (2,000–2,500 kg DM per ha) is often in the range of 180–200 g/kg; the CP content of grass silage is often between 160 and 180 g/kg; and the CP content of hay is between 120 and 150 kg/kg (e.g., Whitehead, 2000). In contrast, the CP content of silage maize is only about 70–80 g/kg. Hence, grass-based diets often contain a surplus of

protein and the magnitude of the resulting high N excretion strongly depends on the proportions of grass, grass silage and hay in the ration and the protein content of these feeds. The protein surplus and the resulting N excretion and NH_3 losses will be highest for grass-only summer rations with grazing of young, intensively fertilized grass or grass legume mixtures. However, urine excreted by grazing animals typically infiltrates into the soil before substantial NH_3 emissions can occur, and overall NH_3 emissions per animal are therefore less for grazing animals than for those housed where the excreta is collected, stored and applied to land.

14. The NH_3 emission reduction achieved by increasing the proportion of the year the cattle spend grazing outdoors will depend on the baseline (emission of ungrazed animals), the time the animals are grazed and the N fertilizer level of the pasture. The potential to increase grazing is often limited by soil type, topography, farm size and structure (distances), climatic conditions, etc. It should be noted that grazing of animals may increase other forms of N emissions (e.g., N_2O, NO_3). However, given the clear and well quantified effect on NH_3 emissions, increasing the period that animals are grazing can be considered as a category 1 strategy to reduce emissions. The actual abatement potential will depend on the base situation of each animal sector in each country. The effect of changing the period of partial housing (e.g., grazed during daytime only) is less certain and is rated as a category 2 strategy. Changing from a fully housed period to grazing for part of the day is less effective in reducing NH_3 emissions than switching to complete (24-hour) grazing, since buildings and stores remain dirty and continue to emit NH_3. Grazing management (strip grazing, rotational grazing, continuous grazing) is expected to have little additional effect on NH_3 losses and is considered a category 3 strategy.

15. In general, increasing the energy/protein ratio in the diet by using “older” grass (higher SSH) and/or supplementing grass by high energy feeds (e.g., silage maize) is a category 1 strategy. However, for grassland-based ruminant production systems, the feasibility of these strategies may be limited, as older grass may reduce feeding quality, especially when conditions for growing high energy feeds are poor, and therefore have to be purchased. Hence, full use of grass production would no longer be guaranteed (under conditions of limited production, e.g., milk quotas or restrictions to the animal density). Therefore, improving the energy/protein equilibrium on grassland-based farms with no possibilities of growing high energy feeds is considered a category 2 strategy.

16. The use of modern protein evaluation systems (e.g., PDI in France, MP in the United Kingdom, DVE/OEB in the Netherlands and AAT/PBV in Scandinavian countries)[14] is recommended (e.g., Van Duinkerken and others, 2011a). In dairy cattle, the use of rumen-protected limiting amino acids, like lysine and methionine, may be helpful to better balance the amino acid composition of protein digested in the small intestine. Because detailed additional information on the behaviour of the feed in the digestive tract is required for a successful introduction of this method, this is considered a category 2 strategy.

17. Shifting N excretion from urea in urine to protein in dung is also an effective measure for decreasing NH_3 loss. Dietary composition should be such that a certain degree of hindgut fermentation is stimulated, without disturbing rumen fermentation. This will shift the excretion of N from urine to dung. Hindgut fermentation can be stimulated by the inclusion of rumen-resistant starch or fermentable fibre that escapes fermentation in the rumen (Van Vuuren and others, 1993). Because in the hindgut acetogenic rather than methanogenic bacteria are present, there is little risk of elevated CH_4 losses. Knowledge about the factors responsible for shifting N excretion from urea in urine to protein in dung is still insufficient and this approach is considered a category 3 strategy.

18. The pH of freshly excreted urine ranges from 5.5 to 8.5, and mainly depends on the electrolyte content of the diet. Although the pH will eventually rise towards alkaline values due to the hydrolysis of urea irrespective of initial pH, the initial pH and the pH buffering capacity of urine determine the rate of NH_3 volatilization from urine immediately following urination. Lowering the pH of urine of ruminants is theoretical possible. However, there are interactions with urine volume, ruminant performance and animal welfare, and it is therefore considered a category 3 technique. Similarly, lowering the pH of dung is theoretically possible, but this might easily coincide with disturbed rumen fermentation and is therefore not recommended. Because of the possible side effects involved this is considered a category 3 technique. Dung consistency could be used to monitor the adequacy of rumen fermentation.

19. Monitoring the protein status is possible with the (calculated) rumen degradable protein balance (e.g., PBV in Scandinavian countries, OEB in the Netherlands) and/or milk urea N (MUN) can be used too (e.g., Van Duinkerken and others, 2011b). MUN should preferably not exceed 10 milligrams per decilitre (mg/dl) (milk urea below 22 mg/dl). Knowledge concerning the factors responsible for variation in MUN is still insufficient, however, and this approach is therefore considered a category 2 strategy.

20. There are also herd management options to reduce NH_3 emissions. First, by increasing the genetic potential of the cows (more milk per cow). This will lead to a higher NUE at herd level because of the lower share of maintenance energy. By equal total annual milk output per country the number of dairy cows and replacement cattle will

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[14] Roughly translated, these acronyms stand for: protein digestible in the intestine (PDI); metabolizable protein (MP); digested protein in the small intestine/degraded protein balance (DVE/OEB); and amino acids absorbed in the intestine/degraded protein balance (AAT/PBV).

consequently decrease. Second, by increasing the number of lactations per cow. This will reduce the number of replacement cattle. Third, the actual number of replacement cattle per dairy cow should be optimized. All three options are a long-term approach, but nevertheless represent category 1 techniques for reducing overall NH_3 emissions. Also, these strategies may have positive animal welfare implications, and likely contribute to a decrease in CH_4 emissions from enteric fermentation as well, especially when expressed in terms of emissions per unit of milk produced (Tamminga, 1996; Kebreab and others, 2001; Powell, Rotz and Weaver, 2009).

21. Rotational corralling of ruminants on cropland may reduce NH_3 emissions and increase N recovery from animal manure compared to the conventional practice of barn manure collection and land application of manure (Powell and Russelle, 2009). Overall results demonstrated that corralling dairy cattle on cropland improves urine N capture, reduces NH_3 loss and enhances manure N recycling through crops. This is considered as a category 2 strategy.

22. Various feed strategies are able to reduce urinary N excretion from housed dairy cattle. A close matching of diets to animal nutritional requirements, feeding only enough protein to meet cows' metabolizable protein requirements, reducing particle size to increase ruminal digestion of grain starch and increasing microbial protein formation (so long as ruminal pH is not depressed), optimizes microbial protein synthesis, maximizes feed N conversion into milk and minimizes urinary N excretion. These are considered as category 2 strategies.

C. Feeding strategies for pigs

23. Feeding measures in pig production include phase feeding, formulating diets based on digestible/available nutrients, using low-protein amino acid-supplemented diets and feed additives/supplements. These are all considered category 1 techniques. Further techniques are currently being investigated (e.g., different feeds for males (boars and castrated males) and females), and might be additionally available in the future.

24. Phase feeding (different feed composition for different age or production groups) offers a cost-effective means of reducing N excretion from pigs and could be implemented in the short term. Multi-phase feeding depends on computer-aided automated equipment.

25. The CP content of the pig ration can be reduced if the amino acid supply is optimized through the addition of synthetic amino acids (e.g., lysine, methionine, threonine, tryptophan) or special feed components, using the best available information on "ideal protein" combined with dietary supplementation.

26. A CP reduction of 2%–3% (20 to 30 g/kg of feed) can be achieved depending on pig production category and the current starting point. The resulting range of dietary CP contents is reported in table AII.3. The values in the table are indicative target levels and may need to be adapted to local conditions.

Table AII.3
Indicative target CP levels in feed for pig rations

Species	*Phases*	*CP content (%)* [a]
Weaner	< 10 kg	19–21
Piglet	< 25 kg	17–19
Fattening pig	25–50 kg	15–17
	50–110 kg	14–15
	> 110 kg	12-13
Sows	Gestation	13–15
	Lactation	15–17

Source: European Commission, 2003.
[a] With adequately balanced and optimal amino acid supply.

27. For every 10 g/kg reduction in CP content of the diet, a 10% lower TAN content of the pig slurry and 10% lower NH_3 emissions can be achieved in growing finishing pigs (Canh and others, 1998b). Currently, the most common CP content of the diet of growing-finishing pigs is approximately 170 g/kg. In experiments, it has been demonstrated that decreases to 120 g protein per kg diet can be achieved without any effect on growth rate or feed efficiency when limiting amino acids are added (= 50% NH_3 emission reduction). In practice, 140 g protein per kg diet is economically feasible (= 30% NH_3 emission reduction, relative to the baseline value with a protein content of 170 g/kg). This can be achieved by phase feeding and adding the most limiting amino acids (Canh and others, 1998b; Dourmad and others, 1993; Lenis and Schutte, 1990). Economically feasible means that the cost of lowering the protein content to 140 g/kg (plus the supplementation with synthetic amino acids) more or less balances the benefits of improved animal performance. Although some work still needs to be done with regard to its practical implementation, this is considered

a category 1 technique for growing-finishing pigs. For sows and weaned piglets additional studies are needed, so for these categories it is considered a category 2 technique.

28. The addition of special components with high non-starch polysaccharide (NSP) content (e.g., sugar beet pulp, soybean hulls) can reduce the pH of pig excreta and thus NH_3 emissions. Increasing the amount of NSP in the diet increases the bacterial fermentation in the large intestine, which results in the immobilization of urea-N from the blood into bacterial protein. Ammonia emissions decrease by approximately 16% when the NSP content of the diet increases from 200 to 300 g/kg, and by 25% when there is an NP increase from 300 to 400 g/kg. However, the effect on NH_3 emissions depends to a certain extent also on the kind of NSP in the diet. Increasing the level of NSP in the diet may also have negative impacts. At high NSP levels, nutrient digestibility decreases and this increases waste production, which is undesirable in animal-dense areas. Furthermore, at increasing NSP levels in the diet VFA concentrations in the manure increase. Although VFAs are not the most important odorous compounds, increased VFA levels may increase odour release from the manure. At increasing NSP levels in the diet, methane production from animal and manure may also increase (Kirchgessner and others, 1991; Jarret, Martinez and Dourmad, 2011). For all these reasons, increasing the amount of NSP in the diet as a means of decreasing NH_3 emissions is considered a category 3 strategy in animal-dense areas and a category 2 strategy in other areas. Moreover, including too much NSP in pig diets can have a negative effect on pig performance and reduce feed conversion efficiency.

29. Replacing calcium carbonate ($CaCO_3$) in the animal feed by $CaSO_4$, calcium chloride ($CaCl_2$) or Ca-benzoate reduces the pH of urine and slurry and the NH_3 emission from the urine and slurry. By replacing calcium (6 g/kg) in the diet in the form of $CaCO_3$ by Ca-benzoate, urinary and slurry pH can be lowered by more than 2 units. In that case, NH_3 emission can be reduced up to 60%. Benzoic acid is degraded in the pig to hippuric acid, which lowers the urine pH and consequently the pH of the slurry stored in the pig house. Benzoic acid is officially allowed in the EU as an acidity controlling agent (E210), and is also admitted as a feeding additive for fattening pigs (1% dosage) and piglets (0.5% dosage) (registered trade mark: Vevovitall). Addition of 1% benzoic acid to the diet of growing-finishing pigs lowers NH_3 emissions by approximately 20% (Aarnink and others, 2008; Guingand, Demerson and Broz, 2005). A similar replacement of $CaCO_3$ by $CaSO_4$ or $CaCl_2$ reduces the pH of slurry by 1.2 units and NH_3 emission by approximately 35% (Canh and others, 1998a; Mroz and others, 1996). Addition of benzoic acid is considered a category 1 technique for growing-finishing pigs and a category 2 technique for other pig categories. Replacement of $CaCO_3$ by $CaSO_4$, $CaCl_2$, or Ca-benzoate is considered a category 2 technique for all pig categories.

30. The effects of the various feeding measures have independent effects on NH_3 emission. This means that these effects are additive (Bakker and Smits, 2002). Combined feeding measures are considered category 2 techniques for all categories of pigs.

D. Feeding strategies for poultry

31. For poultry, the potential for reducing N excretion through feeding measures is more limited than for pigs because the conversion efficiency currently achieved on average is already high and the variability within a flock of birds is greater. A CP reduction of 1%–2% (10 to 20 g/kg of feed) can usually be achieved depending on the species and the current starting point. The resulting range of dietary CP contents is reported in table AII.4. The values in the table are indicative target levels, which may need to be adapted to local conditions. Further applied nutrition research is currently being carried out in EU member States and North America, and this may support further possible reductions in the future. A reduction of the CP content by 1%–2% is a category 1 measure for growers and finishers.

Table AII.4
Indicative target CP levels in feed for poultry

Species	*Phases*	*CP content (%)*[a]
Chicken, broilers	Starter	20–22
	Grower	19–21
	Finisher	18–20
Chicken, layers	18–40 weeks	15.5–16.5
	40+ weeks	14.5–15.5
Turkeys	< 4 weeks	24–27
	5–8 weeks	22–24
	9–12 weeks	19–21
	13+ weeks	16-19
	16+ weeks	14–17

[a] With adequately balanced and optimal amino acid supply.

E. Summary and synthesis and of feeding strategies

32. Low-protein animal feeding is one of the most cost-effective and strategic ways of reducing NH_3 emissions. For each per cent (absolute value) decrease in protein content of the animal feed, NH_3 emissions from animal housing, manure storage and the application of animal manure to land are decreased by 5% to 15%, depending also on the pH of the urine and dung. Low-protein animal feeding also decreases N_2O emissions, and increases the efficiency of N use in animal production. Moreover, there are no animal health or animal welfare implications as long as the requirements for all amino acids are met.

33. Low-protein animal feeding is most applicable to housed animals and less to grassland-based systems with grazing animals, because grass in an early physiological growth stage and grassland with leguminous species (e.g., clover and lucerne) have a relatively high protein content. However, there are strategies to lower the protein content in herbage (balanced N fertilization, grazing/harvesting the grassland at later physiological growth stage, etc.) as well as in the ration of grassland-based systems (supplemental feeding with low-protein feeds), but these strategies are not always fully applicable.

34. Table AII.5 presents ranges of target CP values for various animal categories and for three “ambition” levels of NH_3 emission mitigation. The high ambition values relate to the lowest ranges of CP content for the best feed management practices and low-protein feeding management. These values have been tested many times in research studies and proven to be solid in practice. The medium and low ambition target CP values have been derived from the high ambition targets by simply increasing the target CP content by one percentage point. The achievable ambition levels for housed animals depend on the management skill of the farmer and the availability of the animal feedstuffs with low protein content, including synthetic amino acids.

35. The high ambition values presented in table AII.5 may be difficult to achieve when the feed quality is low (high fibre content and low digestibility of the feed). In these conditions, specific feed additives may help to increase the digestibility. Ruminants and also pigs (especially sows) need minimum fibre content in the feed for proper functioning of the rumen and for welfare reasons.

36. For producing special meat (and milk) products, the recommended protein content of the animal feed for a specific animal category may be slightly above the upper value of the indicated ranges in table AII.5.

37. The economic cost of animal feeding strategies to lower the NH3 volatilization potential of the animal excrements through adjusting the CP content, the cation-anion-balance and the NSP content (e.g., sugar beet pulp, soybean hulls) depends on the initial animal feed composition and on the prices of the feed ingredients on the market. In general, the economic costs range from –€2 to +€2 per kg N saved — i.e., there are potential net gains and potential net costs. Commonly, the economic costs increase when the target for lowering the NH3 volatilization potential increases. The increasing marginal costs relate in part to the cost of synthetic amino acids supplementation relative to using soybeans. The economic costs depend on world market prices of these amino acids and soybeans, but the costs of amino acids supplementation tend to go down. The cost of supplementation of amino acids increases when the target protein content in the animal feed is lowered. This is shown below for feed of fattening pigs (Dr. Andre Aarnink, personal communication, October 2009). Additional information is provided in the a publication by Reis (forthcoming), based on a workshop, “Economic Cost of Ammonia Emission Abatement”, Paris, 25 and 26 October 2010.

Table AII.5

Possible CP levels (percent of dry feed with a standard DM content of 88%) for housed animals, as a function of animal category and for different ambition levels

Animal type	*Mean CP content of the animal feed (%)*		
	Low ambition	*Medium ambition*	*High ambition* [a]
Dairy cattle, early lactation (> 30kg/day)	17–18	16–17	15–16
Dairy cattle, early lactation (< 30kg/day)	16–17	15–16	14–15
Dairy cattle, late lactation	15–16	14–15	12–14
Replacement cattle (young cattle)	14–16	13–14	12–13
Veal	20–22	19–20	17–19
Beef < 3 months	17–18	16–17	15–16
Beef > 6 months	14–15	13–14	12–13
Sows, gestation	15–16	14–15	13–14
Sows, lactation	17–18	16–17	15–16
Weaners < 10 kg	21–22	20–21	19–20
Piglets, 10–25 kg	19–20	18–19	17–18
Fattening pigs 25–50 kg	17–18	16–17	15–16
Fattening pig 50–110 kg	15–16	14–15	13–14
Fattening pigs >110	13–14	12–13	11–12
Chickens, broilers, starter	22–23	21–22	20–21
Chickens, broilers, growers	21–22	20–21	19–20
Chickens, broilers, finishers	20–21	19–20	18–19
Chickens, layers, 18–40 weeks	17–18	16–17	15–16
Chickens, layers, >40 weeks	16–17	15–16	14–15
Turkeys < 4 weeks	26–27	25–26	24–25
Turkeys, 5–8 weeks	24–25	23–24	22–23
Turkeys, 9–12 weeks	21–22	20–21	19–20
Turkeys, 13–16 weeks	18–19	17–18	16–17
Turkeys >16 weeks	16–17	15–16	14–15

Note: These CP values can be used as annual mean targets in low-protein animal feeding strategies.

[a] With adequately balanced and optimal digestible amino acid supply.

Table AII.6

Costs associated with reducing target feed protein concentrations for fattening pigs

Target Protein content (%)	*Extra, costs, euro per 100 kg feed*
15.0	0.00
13.5	0.90
12.7	3.10

List of abbreviations and acronyms

°C	Degree Celsius
ACNV	Automatically controlled natural ventilation
ATMS	Application timing management systems
AU	Animal units
BAT	Best available techniques
BNF	Biological nitrogen fixation
BREF	Best available technique reference document
C	Carbon
Ca	Calcium
$CaCl_2$	Calcium chloride
$CaCO_3$	Calcium carbonate
$Ca(NO_3)_2$	Calcium nitrate
$CaSO_4$	Calcium sulphate (gypsum)
CAPEX	Capital expenditure
Cat.	Category
CH_4	Methane
cm	Centimetre
CO_2	Carbon dioxide
CP	Crude protein
DM	Dry matter
DON	Dissolved organic nitrogen
ECE	United Nations Economic Commission for Europe
EU	European Union
FNEV	Fertilizer nitrogen equivalence values
FYM	Farm-yard manure
g	gram
ha	Hectare
IPPC	Integrated pollution prevention and control
kg	Kilogramme
LECA	Light expanded clay aggregates
Mg	Magnesium
mm	Millimetre
MUN	Milk urea nitrogen

N	Nitrogen
N_2	Di-nitrogen
NH_3	Ammonia
NH_3-N	Ammonia-nitrogen
NH_4	Ammonium
NH_4NO_3	Ammonium-nitrate
NO_3	Nitrate
NO_x	Nitrogen oxides
N_2O	Nitrous oxide
Nsurplus	Nitrogen surplus of the input-output balance sheet
NSP	Non-starch polysaccharides
NPK	Nitrogen-phosphorus-potassium
NUE	Nitrogen use efficiency
OPEX	Operational expenditure
P	Phosphorus
pH	~acidity; negative logarithm of proton (H+) activity
$PM_{2.5}$	Fine particulate matter (< 2.5 micrometre)
PM_{10}	Coarse particulate matter (<10 micrometre)
Ref.	Reference
RI	Roof insulation
S	Sulphur
SSH	Sward surface height
TAN	Total ammoniacal-nitrogen
VFA	Volatile fatty acids
VOC	Volatile organic compound

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‘*Options for Ammonia Mitigation: Guidance from the UNECE Task Force on Reactive Nitrogen*’, represents the culmination of a major effort to synthesize and update available knowledge on the control of ammonia emissions from agriculture to the atmosphere.

The Gothenburg Protocol of the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP) has established national ammonia emissions ceilings together with mandatory ammonia mitigation measures, as described in Annex IX of the Protocol. To provide support to the Parties of the CLRTAP in meeting these commitments, the 17th Session of the Executive Body of the Convention agreed in 1999 to establish an ‘Ammonia Guidance Document’.

The first revision of the ‘Ammonia Guidance Document’ was completed shortly after the entry into force of the Gothenburg Protocol in 2005. Since that time, substantial further information on ammonia mitigation methods, their costs, benefits and practicalities, has become available. Also, a major revision of the Gothenburg Protocol itself has been accomplished, with new emissions ceilings and provisions adopted in May 2012 (Executive Body decision 2012/1). In support of these developments, and in accordance with the Work Plan agreed by the Executive Body, the present revision of the Ammonia Guidance Document has been completed by the Task Force on Reactive Nitrogen.

Reporting to the CLRTAP Working Group on Strategies and Review, the Task Force has “*the long-term goal of developing technical and scientific information, and options which can be used for strategy development across the UNECE to encourage coordination of air pollution policies on nitrogen in the context of the nitrogen cycle and which may be used by other bodies outside the Convention in consideration of other control measures*” (www.clrtap-tfrn.org). This report contributes to this goal, summarizing a wealth of information useful for governments, consultants and agricultural advisers.

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Exhibit 41

Bold Moves on Building Electrification in the San Francisco Bay Area

spur.org/news/2020-12-09/bold-moves-building-electrification-san-francisco-bay-area

December 9, 2020

Photo by *Sergio Ruiz.*

The Bay Area's three largest cities made headlines recently when they passed bold new rules to phase out fossil fuels in buildings. San José, San Francisco and Oakland now have plans to make most new construction all-electric. These actions will make the air cleaner to breathe and slash the region's contributions to climate change.

As the Bay Area's smoke-filled skies made clear this fall, the time for stalling on climate change is past. The next 10 years are critical to put the globe on a path to avert the worst impacts of climate change. California has identified 2045 as the year the state must reach carbon neutrality by balancing emission and removal of greenhouse gasses. Three strategies will greatly reduce greenhouse gas emissions: using less energy, shifting almost all energy usage to electricity, and generating all electricity with renewable sources.

Buildings are a major source of emissions in the Bay Area, accounting for 31% of emissions in San José, 44% in San Francisco and 26% in Oakland. The vast majority of those emissions come from natural gas usage in buildings. Without electrifying buildings and generating that electricity from renewable sources, neither California nor the Bay Area will reach its climate goal of being carbon neutral by 2045.

Electrifying new construction is a least-regrets strategy to reduce emissions. All-electric new buildings generally cost less to build and operate over the lifetime of the building. Eliminating emissions from future buildings is one of the most straightforward strategies for cutting emissions overall.

Reducing reliance on natural gas appliances also makes the air healthier to breathe. Gas stoves and ovens in particular release large amounts of nitrogen dioxide in people's homes, contributing to a host of health problems. A 2013 study showed that living in a home with gas cooking increased children's chance of having asthma by 42%. The impacts of poor air quality are felt most heavily by low-income communities of color, who are already more likely to live in areas with poor outdoor air quality. Natural gas appliances contribute to outdoor air pollution as well. Home use of natural gas added about 14 tons of nitrogen oxides to the atmosphere in 2020. That's a modest slice of total nitrogen oxide emissions in the Bay Area — about 6 percent — but by comparison, it's twice as much as all passenger vehicles generate.

But electrifying new buildings is not sufficient. Over 70% of the Bay Area's building stock was built before 1980, predating even some of California's most basic energy efficiency buildings codes. In a recent study commissioned by the California Air Resources Board, all pathways to reach the state's target of being carbon-neutral by 2045 relied on phasing out new natural-gas appliances between 2030 and 2040. That means that if the state is serious about fighting climate change, we will soon find only electric appliances at the store. Eventually the entire natural gas distribution system can be phased out.

Despite the clear imperative to electrify buildings, state agencies and lawmakers have been lagging on the issue. The California Air Resources Board, California Public Utilities Commission and California Energy Commission all have authority over aspects of natural gas usage in buildings. There has been some progress at these agencies, and the pace is picking up. In its 2019 update to building energy efficiency standards, the California Energy Commission added a compliance pathway for all-electric low-rise buildings. For the 2022 update, the commission is now evaluating how to electrify more buildings and may go as far as requiring new construction to be all electric. And through a combination of funding sources, there's now $400 million available annually to incentivize building electrification. All in all, 2021 looks to be a turning point for state policy to electrify buildings.

To build the momentum on building electrification, cities and counties have stepped up with ambitious policies. As of December 9 2020, 40 local jurisdictions have taken action to reduce reliance on natural gas in buildings, and more than 50 other cities and counties are considering following suit.

The Bay Area has been a leader in this movement. This is due in part to the region's commitment to act on climate. But Northern California has also been able to move quicker on building electrification because its energy provider, Pacific Gas and Electric, supports the phaseout of the natural gas system. The terrain is more difficult in Southern California, which is mainly served by separate electricity and gas providers. For utilities that exclusively provide natural gas, building electrification is a threat to their business model, and gas-only utilities such as Southern California Gas have proven to be hostile to the idea.

San Francisco, Oakland, San José, Berkeley and the Bay Area Air Quality Management District are five of the Bay Area jurisdictions that already have or are contemplating policies to promote all-electric new construction.

Berkeley led the way on electrification, passing the first ordinances in the country to require all-electric new construction. The new rules took effect for projects applying for permits or certificates as of January 1, 2020. The city is currently developing a pathway to electrify existing buildings and expects to have a draft ready for public comment in spring of 2021.

San Francisco has passed two ordinances to date on electrification. One ordinance requires all-electric new construction of residential and commercial buildings and will take effect June 1, 2021. The city allows builders to apply for waivers to allow natural gas for restaurants. An earlier ordinance requires all-electric energy sources when building new municipal buildings or undertaking major renovations. There isn't a plan yet on the table to decarbonize the city's existing building stock.

San Joséprohibited natural gas infrastructure in new detached accessory dwelling units, single-family homes and low-rise multi-family buildings as of January 1, 2020. The city recently expanded the ban with an ordinance to prohibit natural gas in new commercial construction after June 1, 2021. A major debate in San José is whether the city should allow new buildings to connect to the natural gas system for distributed power generation. Some commercial buildings generate their own electricity on site from natural gas using solid oxide fuel cells. Proponents argue that businesses need a backup power source during power outages, and that fuel cells are a better choice than diesel generators. SPUR opposes creating an exemption for businesses using gas-powered fuel cells. Connecting new buildings to gas continues expansion of the natural gas distribution system and creates more costly infrastructure that will either need to be maintained or abandoned as the region moves toward its climate goals.

Oakland City Council voted unanimously to support a ban on natural gas in new construction; the law will come back for final approval on December 15. The Oakland proposal is ambitious, allowing almost no exemptions and going into effect immediately. There is a process to receive a waiver if some aspect of electrification is infeasible, but the builder still has to comply with the requirements in all other respects as much as possible.

The Bay Area Air Quality Management District (BAAQMD) has asked staff to review its rules related to building decarbonization. The air district has authority to regulate pollution of indoor appliances that exhaust to the outdoor air, such as natural gas-burning appliances. Staff members are developing proposals for stronger performance standards for nitrogen oxide emissions from appliances. Clean air and climate advocates are strongly encouraging the district to put in place a zero-emission standard that would effectively require replacement of gas combustion appliances with electric alternatives.

Looking Forward to an All-Electric Future

As more and more buildings are constructed using all-electric technology, more municipalities, states and nations may begin to see that phasing out natural gas in buildings is practical and appealing. Forty years ago, people were skeptical that they could ever enjoy driving a car that got more than 20 miles to the gallon. Today, the average car gets more than 30 miles to the gallon, and electric vehicles are a growing share of the market.

Making the transition to buildings that rely entirely on electricity will require technical ingenuity, creative policies, a consistent dedication to equity and a deep political commitment to reducing greenhouse gas emissions — all of which the Bay Area has in abundance. Over the coming years, the region can fully decarbonize buildings, slash greenhouse gas emissions and air pollution, and serve as a model for the rest of the state and the world.

Exhibit 42

UTILITY DIVE

DIVE BRIEF

California greenlights first-of-its-kind energy code to encourage electrified buildings

Published Aug. 12, 2021

Kavya Balaraman
Senior Reporter

Dive Brief:

- The California Energy Commission (CEC) on Wednesday adopted energy efficiency standards for newly constructed and renovated buildings that stakeholders say are the country's first statewide building code that strongly incentivizes all-electric construction.
- The 2022 Energy Code approved by the commission includes elements that encourage electric heat pump technology for space and water heating, expands solar and battery storage standards, and adopts electric-ready requirements for single-family homes.
- "California's new building energy code takes a major step toward a future where we have healthy fossil-free homes and buildings for all," Denise Grab, a manager with RMI's Carbon-Free Building team, said. While the code doesn't go as far as some clean energy groups had pushed for, "it's a big step in the right direction," Grab added.

Dive Insight:

The CEC's 2022 code update is part of a three-year cycle in which the commission adopts standards to increase the energy efficiency and lower the emissions produced by buildings in California. The code is now headed to the California Building Standards Commission and, if approved by that agency, will come into effect at the beginning of 2023.

The 2022 Energy Code is the product of multiple stakeholder meetings, workshops and more than 300 public comments, according to the CEC. The "star" of the 2022 Energy Code, said Will Vicent, a manager at the CEC's Building Standards Office, is heat pumps.

"Used in the right applications, electric heat pumps provide substantial increases in energy efficiency, drastic reductions in greenhouse gas emissions and provide opportunities for load flexibility — all while being cost comparable to other prevalent systems in the market," Vicent said.

The update adopted by the CEC would include heat pumps as a performance standard baseline for water or space heating in single-family homes, and space heating in multi-family homes, as well as certain commercial buildings, Vicent said. In addition, it would adopt "electric-ready" requirements for single-family homes, meaning they would need to have dedicated circuits and other infrastructure that would easily enable electric appliances to be installed in the future.

The CEC estimates that the 2022 Energy Code will result in $1.5 billion in consumer benefits over the next three decades, as well as reducing 10 million metric tons of greenhouse gas emissions.

RMI and other stakeholders have been urging the CEC to set energy standards that would effectively require all new buildings in the state to be built with electric appliances, Grab said. While the

CEC didn't end up going that far, its approved code update is still a significant development, she added — as the first statewide building code that incentivizes all-electric construction to this extent, it sets the bar for other states' ambitions, and "it can really set off an avalanche," she explained.

Other stakeholders agreed. In putting together the 2022 Energy Code, the commission managed to thread the needle of legal authority, market readiness and customer choice "and come out the other end with what will be, if adopted, the strongest state decarbonization code in the country," said Panama Bartholomy, executive director of the Building Decarbonization Coalition, at the CEC's meeting on Wednesday.

The move was also welcomed by state utilities, including Southern California Edison, which filed a letter with the commission this week voicing its support for the standards. In addition, SCE urged regulators to consider a 2025 code update that will "fully electrify new construction in order to accelerate efforts needed to be on a path to achieve California's 2030 decarbonization target."

"We welcome the opportunity to support the California Energy Commission's efforts to advanced efficient, all-electric new construction when it is feasible and cost-effective," Pacific Gas & Electric (PG&E) spokesperson Lynsey Paulo said in an emailed statement.

In terms of the impact of additional electrification on the grid, Paulo said PG&E continuously forecasts load in its service area and implements upgrades to the distribution grid to meet demand.

"PG&E fully expects to meet the needs that all-electric buildings will require," Paulo added.

"Fighting climate change requires the widespread adoption of multiple strategies and technologies to reduce greenhouse gas emissions – everything from stronger building codes and transportation electrification to energy storage and hydrogen innovations," San Diego Gas & Electric (SDG&E) said in a statement.

Exhibit 43

To fight climate change, Ithaca votes to decarbonize its buildings by 2030

npr.org/2021/11/06/1052472759/to-fight-climate-change-ithaca-votes-to-decarbonize-its-buildings-by-2030

Deepa Shivaram

Solar farms surround trees at Cornell University in Ithaca, N.Y. The city voted Wednesday night to decarbonize the city's buildings and install more energy efficient appliances and more solar panels. The city says the move will cut 40% of their carbon emissions.

Heather Ainsworth/AP

In a groundbreaking move this week, the city of Ithaca, New York, voted to decarbonize and electrify buildings in the city by the end of the decade — a goal that was part of the city's own Green New Deal and one of the portions of the plan that will help the city become carbon neutral by 2030.

Ithaca is the first U.S. city to establish such a plan, which the city says will cut Ithaca's 400,000 tonsper year of carbon dioxide emissions by 40%. The timeline to achieve its goal is much sooner than what other cities around the world have pledged to do.

Ithaca's move away from natural gas and propane comes amid a broaderpolitical battle over the shift to renewable energy. In more than a dozen states, lawmakers backed by the gas industry have fought local efforts to ban gas hook-ups and electrify buildings. In Ithaca, though, New York State Electric and Gas says they are working with the city in their efforts to decarbonize.

"To fight climate change, we need to reduce carbon emissions," Luis Aguirre-Torres, the city's director of sustainability, told NPR. "The entire world is looking at 2050. [Ithaca] was looking at 2030, so it was an incredibly difficult thing to achieve."

The process of decarbonization and electrification of buildings in the city will mean installing solar panels and replacing natural gas stovetops with electric ones. It'll also involve installing more energy efficient heat pumps.In June, the city passed legislation saying that newly constructed buildings and buildings being renovated are not allowed to rely on natural gas and propane, which means the entire city will move away entirely from natural gas and propane, Aguirre-Torres said.

"I believe we are the first in the world to attempt something so crazy, to be quite honest," he said.

Aguirre-Torres said Wednesday night's vote is worth celebrating because of their unique accomplishment — but he's also celebrating how replicable he believes this project is.

"We demonstrated this works and it can be replicated all over the United States."

Researchers say it's an ambitious timeline

Timur Dogan from Cornell University is one of the researchers helping the city of Ithaca with its efforts to become carbon neutral.

He said cutting down on how much energy buildings use, rather than focusing on other emissions is "low hanging fruit" — it's easier to accomplish because the technology to fix it already exists. And the impact is significant.

"More than 40% of the global greenhouse gas emissions are produced or somewhat related to buildings, with heating with gas or fuel oil and the electricity that buildings are using," Dogan said.

The timeline to make the city carbon neutral by 2030 is a "very ambitious agenda," he said. Since last summer, Dogan has been gathering data to help the city through the process and will present his findings to the city in the next few months.

A "social restructuring" in the fight for climate change

For Aguirre-Torres, the vote to decarbonize is significant in itself, but he's also excited about who is doing the work behind the scenes with him.

BlocPower, a Brooklyn-based climate-tech startup, was selected to partner with the city of Ithaca in 2019 in the plan to decarbonize its buildings. BlocPower, founded by Donnel Baird, primarily works with low-income communities and communities of color to achieve safer and healthier decarbonized buildings.

Aguirre-Torres, who is Latino, says working with Baird and others at BlocPower gave him a lot of hope, especially while working in a city such as Ithaca, which is predominantly white.

Data shows those working the environmental movement are overwhelmingly white. The work he and Baird's team are doing in Ithaca also shows a "social restructuring," he says.

"When you think about the demographic composition of upstate New York ... and then you have a brown dude like me and a couple of Black guys at BlocPower driving this transformation, it gives you hope that a lot of things are happening not only that are technological and financial. There is a social restructuring happening in our community," he said.

"At the core of everything is this structural change that we're witnessing and I think it's a beautiful, beautiful thing."

Exhibit 44

New York City is banning natural gas hookups for new buildings to fight climate change

cnbc.com/2021/12/15/new-york-city-is-banning-natural-gas-hookups-for-new-buildings.html

December 15, 2021

- The New York City Council on Wednesday voted to pass legislation banning the use of natural gas in most new buildings.
- Under the law, construction projects submitted for approval after 2027 must use sources like electricity for stoves, space heaters and water boilers instead of gas or oil.
- The bill would cut about 2.1 million tons of carbon emissions by 2040, equivalent to the annual emissions of 450,000 cars, according to a study by the think tank RMI.

Michael Brochstein | LightRocket | Getty Images

The New York City Council on Wednesday voted to pass legislation banning the use of natural gas in most new construction, a move that will substantially slash climate-changing greenhouse gas emissions from the country's most populous city.

The bill now goes to Mayor Bill de Blasio's desk for signature. Once signed, the measure will go into effect at the end of 2023 for some buildings under seven stories, and in 2027 for taller buildings. Hospitals, commercial kitchens and laundromats are exempt from the ban.

Under the law, construction projects submitted for approval after 2027 must use sources like electricity for stoves, space heaters and water boilers instead of gas or oil. Residents who currently have gas stoves and heaters in their homes will not be impacted unless they relocate to a new building.

New York state was the sixth largest natural gas consumer in the country in 2019, according to the U.S. Energy Information Administration. While the state's electricity today comes primarily from natural gas, which generates carbon dioxide emissions when burned, nuclear power and hydroelectricity are also significant sources, supplying 29% and 11% of generation in 2020, respectively — and neither of those power sources generate carbon dioxide emissions. Moreover, the state's grid will continue to become cleaner during the transition to renewable energy sources.

Buildings in New York City account for about 70% of its greenhouse gases. Today's ban will likely push forward a New York state requirement to obtain 70% of its electricity from renewable sources like solar, wind and water power by 2030 and achieve a net-zero emissions electric sector by 2040.

"If the largest city in America can take this critical step to ban gas use, any city can do the same," Mayor Bill de Blasio said in a statement. "This is how to fight back against climate change on the local level and guarantee a green city for generations to come."

The bill will cut about 2.1 million tons of carbon emissions by 2040 — equivalent to the annual emissions of 450,000 cars — and save consumers several hundred million dollars in new gas connections, according to a study by the think tank RMI.

The ban will also minimize the risk of gas explosions and reduce exposure to air pollution that poses health risks to residents, particularly low-income communities of color that are disproportionately exposed to pollution.

Similar policies have been debated across the country. A few dozen cities, including San Francisco, Berkeley and San Jose in California; Cambridge, Mass.; and Seattle, have moved to ban natural gas hook ups in some new buildings as a way to combat climate change.

However, states like Texas and Arizona have barred cities from implementing such changes, citing that consumers have the right to pick their energy sources.

Real estate groups, the oil and gas sector and the National Grid — the utility that provides the city with natural gas — have strongly opposed the bill, arguing that it will cause a spike in demand for electricity that could prompt winter blackouts.

Opponents also argue that the legislation will prompt higher costs for buildings that use electricity for heat compared to those that use natural gas.

“The real estate industry is committed to working with policymakers to develop proven policies that meaningfully reduce carbon emissions from the built environment,” said James Whelan, president of the Real Estate Board of New York, a trade association for the city’s real estate sector.

“While we appreciate that the efficient electrification of buildings is an important component of realizing these goals, these policies must be implemented in a way that ensure that New Yorkers have reliable, affordable, carbon-free electricity to heat, cool and power their homes and businesses,” Whelan said.

“National Grid shares New York’s goal for economy-wide decarbonization,” the company’s spokesperson Karen Young said in a statement. “We recently announced the progress we’re making with our own decarbonization plan to transform our networks to deliver smarter, cleaner and more resilient affordable energy solutions.”

Michael Giaimo, Northeast regional director of the American Petroleum Institute, an oil and gas lobbying group, said the bill was “rushed through the legislative process without adequate review, analysis or debate.”

“With additional time and study, we believe the Council will better appreciate the impact of enhanced electrification as well as the importance of a diverse energy mix,” Giaimo said. “Hydrogen and renewable natural gas can play a critical role in furthering the city’s emission reduction goals while maintaining affordability and preserving consumer choice.”

Con Edison, the city’s other major utility company that provides electricity in addition to gas, has been a proponent of the bill along with some sustainable building groups and energy analysts. Supporters have argued that the city’s grid is well equipped to handle an increase in electricity demand.

Environmental groups celebrated the vote Wednesday and urged New York state and the country to follow in its footsteps.

“America’s biggest city is serious about climate change, and today proves it,” said Alex Beauchamp, Northeast Region director of the environmental group Food & Water Watch.

“With a gas free NYC, we can deliver better public health outcomes and make real strides to cut climate-warming emissions,” Beauchamp said. “Next up, New York state and the nation must follow suit.”