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Alternative Farming Systems, Biotechnology, Drought Stress and Ecological Fertilisation

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Alternative Farming Systems, Biotechnology, Drought Stress and Ecological Fertilisation

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Thinking by Connections and the Dynamics of Nature for Food Production

Clara Ceppa

Abstract So far human development has been based on the accelerated exploitation of resources such as air, water, and earth, from which most human resources derive. Until recently those global commons were considered valueless and were therefore exploited in the belief of unlimited availability. Recently, the accumulation of major environmental issues has challenged this behaviour. On one hand we are witnessing the continuous rise in the price of raw materials and a strong demand for recyclable materials, while on the other hand we are producing more waste. Hence we should not expect Earth to produce more but we should do more with what Earth produces, and adopt a sustainable waste management. We must wake up to the fact that the growing mass of waste generated by industrial activities is becoming critical because it causes serious damage to human health and the environment. We must start to consider wastes like resources and be inspired by Nature, where surpluses are metabolized by the system itself. If we adopt this principle in production, it will favor the development of zero-emission production, because the waste – or output – of one process is used as a resource – or input – for another production process. This leads us to a change of perspective that goes in the direction of thinking by connections. Thinking by connections means for instance that industries organize themselves into local sustainable networks. In such networks waste products from one industry is sold as a resource to another industry, and thus benefits both of them. In these systems the flows of material and energy generate internal connections. Waste enriched with new values becomes a resource and is available for producing new products strictly connected to the local know-how. By applying the systemic approach the cultural identity of the territory where the crops are grown is reinforced, the biodiversity is conserved and the quality of the products generated is improved. This concept of thinking by connections therefore creates positive effects on the territory in both environmental and economic terms.

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1 Introduction

Capitalistic development has primarily been based on the accelerated exploitation of all resources, human and natural (Zorzoli 1985): water, air and earth, indispensable resources for human survival, seemed to have no value and were exploited in the belief of unlimited availability (Ceppa et al. 2008). In classic economic theory, in fact, these three elements were considered resources available to humanity at no cost. However, the accumulation of environmental problems has challenged this theory: the bad smell of air and rivers, urban smog and the excessive growth of algae have demonstrated that clean air and water must be valued. Currently these resources cannot be considered free for the taking (Gerstenfeld 1994).

While we tend to deal daily with solid urban waste by means of differentiated collection, we pay less attention to the waste produced by agro-food sector. This occurred because we have always thought of production processes as a linear sequence of actions, independent from one another, implemented to produce a commodity. Moreover most farms use enormous amounts of synthetic fertilizers and pesticides because these are viewed as far removed from our personal lives. Nonetheless the mass media are now focusing more on the impact and extent of this phenomenon, even on our daily life. This ecological assessment must be followed by an economic assessment: the aforementioned residues contain a significant amount of intrinsic properties and potentials that were not exploited but they were dumped or drained off into sewers and water courses. However, the resources saving, viable through a recovery of byproducts, leads to the enrichment and diversification of the industrial apparatus of the farming and food sector. Therefore it becomes urgent to devise new forms of agriculture; a new agriculture that introduces sustainable methods to distribute the resources not yet annihilated by agro-industrial methods: biodiversity, age-old skills and methods.

2 Environment: State of Art

The pressure of humans on natural resources in the last half-century has become more intensive and widespread than ever (Boggia and Pennacchi 2003): in the past 50 years humans have changed ecosystems more rapidly and extensively than in any other comparable period of human history, mainly to meet the growing demand for food, water, timber, fiber and fuel. This production effort has stressed the Earth to such an extent that water resources are now scarce; biodiversity is diminishing before our eyes, especially agro-biodiversity, with a systematic reduction of animal breeds and plant varieties that for centuries have contributed to sustaining entire areas in a Human-Nature union that was perfectly sustainable; lands have died or become desertified due to the excessive use of chemicals.

Today agriculture consists of the intensification of a few crops, all at the cost of losing that magnificent genetic diversity resulting from millennia of trial and error. Actual extensive monoculture (Deb 2004) eliminates both the good and bad grasses and, to make room for itself, it eliminates the flora and fauna belonging to the ecosystem into which the monoculture is introduced: woods, hedges, beneficial insects, birds, amphibians. All of these disappear to be replaced by countless hectares of vineyard, olive groves and corn fields (Petrini 2005). The sundry book *Fatal Harvest* (Kimbrell 2002) provides statistics on the decline of biodiversity in the United States: "between 1902 and 1983: 80% of tomato varieties became extinct; 93% of lettuce varieties, 86% of apples, 90% of corn and 96% of sweet corn. Of the more than 5,000 existing varieties of potatoes, only four make up the overwhelming majority of those cultivated for commercial purposes in the United States. Two types of peas occupy 96% of American crops and six types of corn, 71% of the total".

Agriculture has a substantial impact on the environment in developing countries and industrialized countries alike. The major problems caused by agriculture are soil erosion, salinization and pollution caused by pesticides and fertilizers (Boggio et al. 2008) which also spoil the ground water. We are talking about a sector that is a widespread source of pollution because it spreads pollution throughout the territory. In this case too, sometimes due to a lack of technical know-how, there is a tendency to overutilize certain products, e.g. pesticides, without taking into account the externalities that unwise use can cause (Lanza 2002).

The breakpoint has long been surpassed so it is clear that we must take a radical change of course and adopt a profound change in our mentality: agriculture must be deindustrialized and it must be our priority to restore the Earth, natural farming environment and biodiversity. Life on our planet is linked to biodiversity and the existing connections between various forms of life: our own survival depends on the natural abundance of biodiversity.

3 Possible Solutions

The time has come to realize that our current productive activities squander most of the resources they take from Nature. To give an example, when we extract cellulose from wood to make paper, we cut down an entire forest but use only 20–25% of the trees while the remaining 70–80% are discarded as waste. Palm oil makes up only 4% of the overall biomass of the palm tree; coffee beans make up only 4% of coffee bushes. Breweries extract only 8% of the nutritional elements contained in barley or rice for fermentation (Capra 2004). It's happening because the current setup of production is "linear": the process is a sequence of independent phases unconnected to each other and the raw materials mainly come from third countries.

The focus of production is mainly on the "product" and not on the "process": this setup prevents a vision of the production process in its entirety and consequently hides the possible connections there may be between the phases within a given process or between two different production processes. These incur a cost to the environment but also economic and social costs to the entire community. We have to consider that the waste from production processes, currently thrown away and not valorized, abound in precious resources for other manufacturing activities; hence we should not expect the Earth to produce more but we should do more with what the Earth produces (Pauli 1996) and we should learn from Nature (Benyus 1997) system where there is not the concept of waste.

Underlying this attitude of respect and reverence for Nature is a philosophical orientation that does not consider human beings above or beyond the natural world and does not attribute an exclusively instrumental or utilitarian value to Nature but considers the living world as interconnected and interdependent and recognizes the intrinsic value of all living beings. This school of thought is called “deep ecology” (Capra 1996). Deep ecology fully expresses the meaning of Oikos, the “Earth family”, which is the Greek root of the word “ecology”. Humanity also belongs to Oikos along with plants, animals and microorganisms, and humans should therefore behave in a way that does not interfere with the intrinsic capacity of the global community of living beings to sustain life through a vast network of relations that for the last three billion years has evolved and diversified itself without ever going awry (Capra 2004).

This is the essential meaning of ecological sustainability: the concept of sustainability was introduced at the beginning of the 1980s by Lester Brown, founder of the Worldwatch Institute, who defined a sustainable society as “a society that is able to meet its own needs without harming the opportunities of future generations” (Brown et al. 2001). Several years later, the Report of the World Commission on the Environment and Development (the Brundtland Report) used the same expression to illustrate the notion of sustainable development: “Humanity has the capacity to achieve sustainable development, i.e. satisfy the needs of the present without harming the opportunities of future generations to meet what will become their own needs”. (Capra 2004).

The key to reach an operative definition of ecological sustainability are found in understanding the fact that sustainability does not refer to a state of immobility but a dynamic process of co-evolution. The first step to take in our effort to build sustainable communities must be that of becoming “ecologically literate” (Capra 1996); in other words we must make an effort to understand the organizational principles common to all the living beings which ecosystems have developed for the purpose of sustaining the web of life and use them as guidelines in the construction of sustainable human communities and open industrial systems where the scraps of one process become resources for another process.

Observing Nature and imitating it means humbly recognizing our dependency on it and our non-priority role in the web of life in which we interact, as a specific individuality, with an enormous number of living systems. Humans are only one part of that complex fabric of interactions which is Nature, live within it and depend on it (Barbero and Campagnaro 2008). It is necessary to create an ecocompatible society based on a lifecycle of products that is consistent with the environmental needs and equipped with a socioeconomic apparatus capable of responding to human needs while consuming few resources (Lanzavecchia 2000). If we stop and think that over 90% of the water used in a brewery does not end up in the bottle, and over 20% of the grain after threshing is buried, we can understand how dramatically urgent it is to start practicing this principle (Pauli 1996).

In response to this situation today there is a new science emerging called agroecology which is essentially based on the supposition that ecosystems, as they are, have all the internal means they need for self-regulation and automatically carrying out operations such as recycling nutrients or fighting against harmful insects and disease (Petrini 2004). A good definition of agroecology is provided by Miguel Altieri (Petrini 2005), Professor of Agroecology at the University of Berkeley: "… agroecology seeks a format of dialogue between different kingdoms, traditional know-how and Western science, and puts them on the same level."

In fact cultivating crops and breeding animals requires a gentle handling of them and the environment and a respect for the local biodiversity, the traditional know-how and the rhythms of Nature. Autochthonous varieties and breeds are preferable because their survival guarantees the biodiversity that allows the natural system to self-regulate in the best way possible. Safeguarding territorial biodiversity and developing local resources leads to the generation of a balanced social and economic system that responds to needs for well-being of the people living in that setting according to the rhythms of natural cycles (Bistagnino 2008c).

4 Systemic Design to Apply to Industry the Dynamics and Cycles of Nature

In a world of growing complexity like the one we live in today it is becoming ever more obvious that the economic, environmental, technological, political and social problems of our times are systemic and cannot be solved within the current fragmented and reductionist model of our academic disciplines and our social institutions (Capra 2007). Therefore we must turn to Nature, the System par excellence, to understand the complexity of a system made up of relations between different beings and the continuous evolving flow of matter; moreover in Nature there is no such thing as waste and even surpluses are metabolized by the system itself.

If these conditions, which are fundamental for a living system, are adopted in production, they will favor the development of a zero-emissions production precisely because the waste (output) of one process is used as a resource (input) for another production process. This leads us to a change in perspective that goes in the direction of thinking by connections (Barbero and Campagnaro 2008). Therefore the production process will no longer be seen as a sequence of actions independent of each other but will be considered in its entirety.

The systemic concept is based on a model that recognizes a reality made up of qualities that are often not quantifiable, connections that are apparently invisible but indispensable for life, not "things" but systems of relations that give concreteness to that which we observe, from the infinitely small to the infinitely large: electrons, atoms, cells, tissues, organs, living species, social communities, ecosystems. Each of these is a complex system that exists by virtue of the relations among its components that live on the basis of connections with other equal systems and the reciprocity that joins them to a specific context. Relations between the whole and its parts, between the whole and that which "contains" the whole, subjected to constant redefinition according to nonlinear dynamics. However we must avoid thinking that the systemic philosophy is unripe and immature. Its origins involved the likes of Leonardo da Vinci whose studies were based on the systematic observation of Nature, the importance of relationships and the description of phenomena. And this was at least 100 years before the mathematics and mechanistic concepts of Descartes and Galileo. In *The Science of Leonardo* Fritjof Capra, defines this great man as the "ante litteram systemic thinker" who observed everything, from the gears of machinery to the muscles of the human body, from the dynamics of water in motion to the study of air flows, including sound in relation to the shape of musical instruments. His way of intellectually knowing phenomena was to analyze the context and ascertain the possible cause-effect relationships between the natural forms and anatomic structures of animals. Four hundred years later Einstein's theories of the quantum and relativity restored a meaning to Leonardo's intuitions with the necessary "corrections", and made a tremendous contribution to going beyond mechanistic thought in favor of an ecological paradigm. From that moment on – and we are talking about the beginning of the twentieth century – systemic thought occurred and developed almost simultaneously in many different disciplines, from "shape" psychology to biology up to and even after after World War II in the theory of Cybernetics (Barbero and Campagnaro 2008).

For Leonardo da Vinci understanding a phenomenon meant putting it in relation to another phenomenon through an infinity of patterns and observations. Many of these were taken from Nature, whose exceptional genius and creativity he admired to the point of stating that "in its inventions nothing is lacking and nothing is superfluous" (Capra 2007). This attitude of seeing Nature as a model and a guide has been adopted today by systemic designers who study patterns and flows in the natural world and attempt to incorporate those principles to design and production methodologies (Capra 2004). Therefore we retrieve the cultural and practical capability to delineate and program the flow of material from one system to another in a continuous metabolization that reduces ecological impact and generates a notable economic flow (Bistagnino 2008b).

Even in the science disciplines of the past 25 years there has been a new systemic understanding of life according to its organizational models and basic processes. It is the constant flow of energy and matter through a web of chemical reactions that allow a living organism to generate, repair itself and endure (Greco and Scaffidi 2007).

Until today people always thought of the production process as a sequence of actions independent of each other for the purpose of producing goods; however, unfortunately, this model creates a substantial amount of waste (Ceppa 2008c). Currently the focus of project is on the product and on the quantity produced, but often this is to the detriment of quality: in a little more than one century, along with the industrialization process, a sort of technocratic dictatorship has been established in which economy prevails over culture, profit prevails over politics and quantity is the major, if not the only, yardstick for human activities (Petrini 2005). It becomes necessary to give up the exclusive focus on the product and the product lifecycle and extend our gaze, and therefore our competence, to the entirety of relationships generated by the production process (Bistagnino 2008b).

The vision of systemic design challenges current industrial organization and frees itself of a consumerist approach that focuses exclusively on the product. Systemic design proposes a new paradigm that considers humans the center of an "ecological context" and recognizes the interdependence between social and natural structures: a scenario in which the role of life becomes essential once again, in biological and cultural terms alike (Bistagnino 2008a).

This new paradigm rejects the dominant anthropocentrism of Western culture and seeks the foundations for a renewed and more balanced relationship with Nature (Bartolommei 1995). The approach of systemic design can activate a new economic model based on the planning of open production cycles; it is a methodology applies to industry the dynamics and cycles of Nature. Productive activities can reflect the way Nature functions. In Nature has no waste and its surpluses are metabolized by the system (Bistagnino 2008b).

Today it is precisely environmental degradation, the lack of resources and the myth of unlimited development that have forced us to think about and reconsider the role of humans in society. We do not play the role of director but rather we are part of an interconnected and interdependent system. Being aware of this means thinking and acting to create a sustainable future in which we can meet the needs of everyone without jeopardizing the needs of generations to come (Pellizzoni 2001), not only in terms of material resources but also in terms of cultural diversity and growth. This requires a radical change in our perception of reality, starting with a redefinition of the basic values shared by society (Balbo and Signori 2008).

5 Case Study

5.1 Fruit Growing: Current Situation

The systemic approach, or Systemic Design, is extensive and can be applied to various production sectors.

In specific terms I would like to mention the case study on fruit growing in Piedmont (Italy) in the district of Cuneo. It is characterized by the monoculture of peaches occupying 4,716 hectares of land, apples occupying 3,297 hectare and pears occupying 740 hectares. Each apple tree produces approximately 32 kg of apples, each peach tree 22 kg of peaches and each pear tree 30 kg of pears.

These three production lines (Fig. 1) are comparable to each other and therefore can be analyzed together. The productive systems are then observed on the basis of

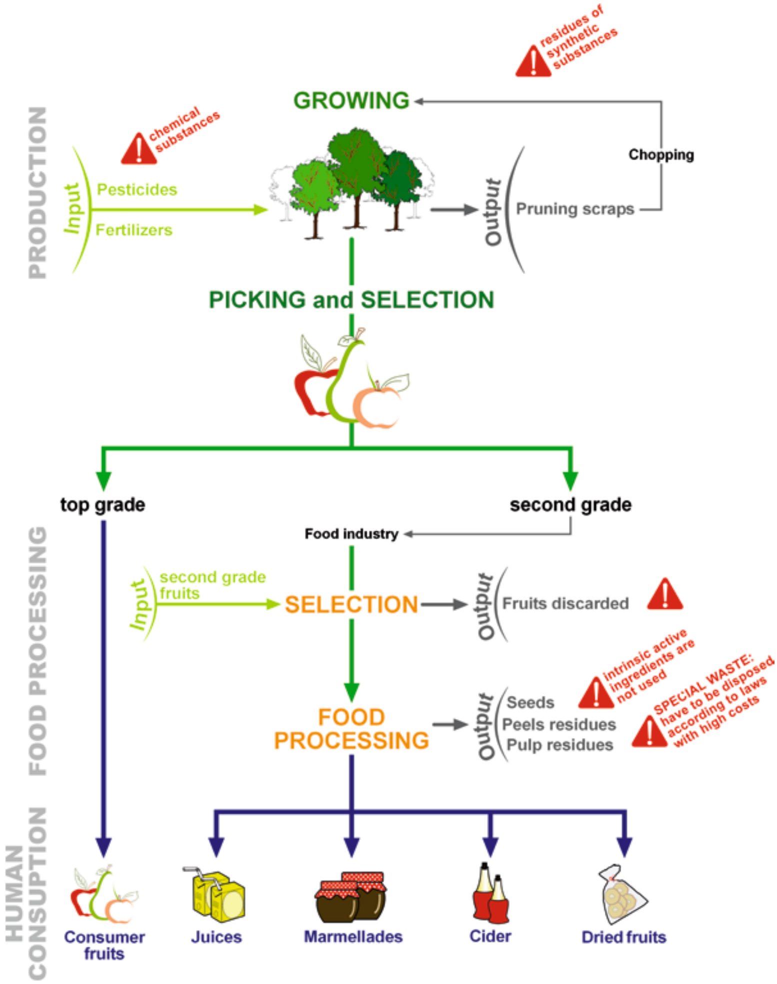

Fig. 1 Scheme of the current linear productive process; every productive phase needs resources and produces wastes. Moreover the problems are pointed out

their induced internal and external relations: procurement and conversion of the material, management of the output on a territorial level, the use of energy, control of emissions. The system is then redesigned to make them ramified, complex, multipolar and strongly related to the territory. This approach affords a view with renewed and extremely important theme-related perspectives such as access to raw materials (Barbero and Campagnaro 2008).

Analysis of the first phase of the production chain, cultivation, clearly shows a notable use of chemical pesticides, weed killers and insecticides to protect the trees from potential disease and external enemies. However, these substances also lower the quality of the product. Traces of synthetic substances remain on the fruit and weaken the health of the humans who consume it (Ceppa 2008b). Subsequently the pruning scraps are chopped up and scattered on the land to fertilize it but, since they are contaminated by these residues of synthetic substances previously used on the trees, they significantly contaminate the soil.

It is important to note that the current production sequence produces scraps that are considered ‘special’ by Legislative Decree No. 152 2006 now integrated by Legislative Decree No. 16/01/08 no. 4, Italy. Special waste must be eliminated according to particular regulations with extremely high costs. If they are brought to the landfill they would increase the amount of leachate into the land. This waste consists of all the fruit discarded during the selection phase because it does not fulfill the assessment criteria, in addition to the peels, seeds and pulp residues deriving from various processes for producing nectars, juices and purees. Throwing away this waste also means not using intrinsic active ingredients that are rich with potential benefits. What is absurd and contradictory is that these active ingredients are created synthetically in the cosmetics and pharmaceuticals industry.

It is therefore clear that now significant amounts of usable material is stocked at the dumps or eliminated in a way that causes a negative impact on the environment and high overheads. It is equally undeniable that even in this productive sequence the focus of the production is on the product, or rather on the quantity of the product and not on its quality. We have to change this view and put humans at the center of the entire question. In this way we would offer quality products that are enriched with ethical and social values (Ceppa 2008a).

5.2 Fruit Growing: Systemic Approach Application

We must start with the realization that organic waste thrown away and not valued contains large quantities of precious resources for other manufacturing processes. The Systemic Design leads industries to organize themselves into local sustainable groups in such a way that the waste products of one can be sold as a resource to another and benefit both of them (Pauli 2000). Ecodesigner Michael Braungart (Germany) and William Mc Donough (USA) (1998) state that in order to build sustainable industrial societies, the principle of ecodesign and the cycle of material resulting from it must be extended beyond the simple sphere of organic waste. Waste enriched with new values becomes a resource and made available for producing new products strictly connected to the local know-how (Barbero et al. 2008).

The availability of new resources drives research to find new fields of application suitable to the territory being analyzed; in fact, by applying the systemic approach we can see how the cultural identity of the territory where the crops are grown is reinforced, the biodiversity is conserved and the quality of the products generated is improved (Bistagnino 2008a). This creates positive effects on the territory in both environmental and economic terms. Seeing the entire production chain from the systemic perspective allows us to completely reutilize the output. So the pruning scraps are completely reutilized after being chopped: one part is used to create the substrate for growing autochthonous varieties of mushrooms, for

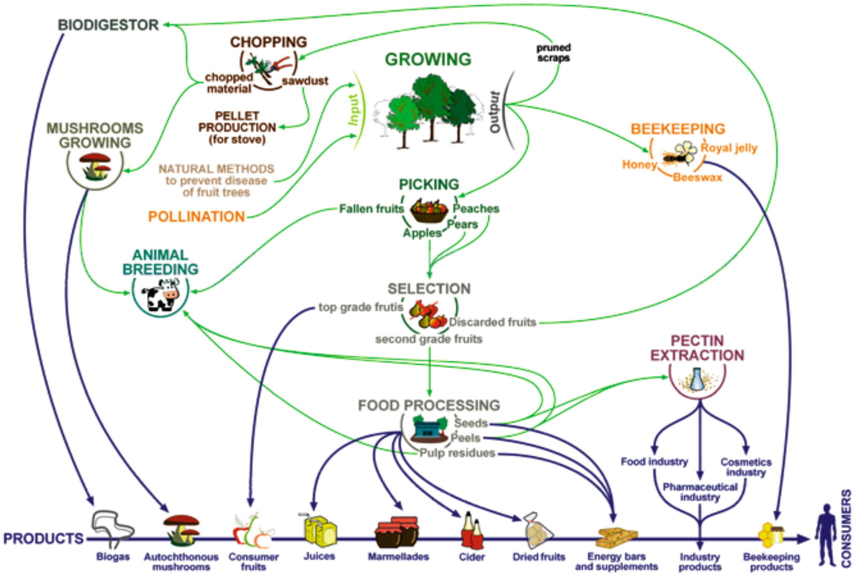

Fig. 2 Scheme of the new system proposed: flows of material and new products are put in evidence

human consumption and animal feed (e.g. cattle, pigs) in a rediscovery and reinforcement of local traditions (Fig. 2). Another portion becomes sawdust and the remaining portion is put into a biodigestor to produce biogas.

An interesting proposal is systemic cultivation that does not use any synthetic pesticides but natural methods that are equally effective. These methods exploit the beneficial behavior of insects, birds, herbs, fungi and bacteria to keep disease away from the plants being cultivated. These can prevent disease of fruit trees. According to this method the fruit trees are planted next to host trees and flowers that attract insects which are harmful to fruit. This method produces high quality products that are completely natural with no traces of chemical substances harmful to humans.

The fruit that falls from the trees, which today is not picked up but left to rot on the ground, is used to feed livestock. Moreover the output deriving from the food processing industry is totally reused in other processes. The discarded fruits are put into a biodigestor, the pulp residues along with the peelings and seeds are used to produce energy bars and supplements for human consumption and food for feeding pigs and cattle (Ceppa 2008c). The peels and seeds from the cleaning of the fruit can be used to extract a percentage of pectin, a valuable organic compound used in the food, pharmaceutical and cosmetics industries.

Interesting fields of application for these new materials, available but previously considered waste, give them value and make it possible to obtain more products from any given field with the same amount of land area and number of trees than the current linear system does. All of this was possible because the outputs were considered raw materials filled with potential: this allows the so-called scraps to become materials worthy of proper, rational and targeted management for being reused as raw materials for other production processes. All of this was made possible thanks to a change in perspective for viewing the problem. The systemic approach produced higher economic profits and better quality products abounding in vital social and ethical values because attentive to human and animal health as well as respect for the environment. We can see its benefits to the environment and the economy, benefits generated by a possible transition towards a systemic nonlinear type of productive and territorial culture.

6 Conclusion

The perspective of systemic design requires take a closer look at our current industrial model and remove it from a consumerist vision that exclusively sees the product. Then we can propose a new paradigm that considers humans the center in an "ecological context" which recognizes the interdependence between social and natural structures. The presented project concretely integrate production culture and design research in order to reveal the connections and congruencies, today still hidden, between artificial production and Nature; the application of the systemic approach in these areas enables us to reconsider the current industrial setup and distance ourselves from the consumerist vision, associated exclusively with the figure of "the product." The sustainability "indicators" in a sustainable production system are not economic growth, development or competitive advantage but the entire lifecycle of the product and the way it relates within the context in which it is located. The aspirations of our generation and the opportunities/possibilities for future generations depend on these sustainability factors. Sustainable production must correspond to sustainable consumption: the task of design is to realize and verify this correspondence and pursue it when developing products and services. Systemic Design methodology can help us to reduce the pressure of human activity on the environment: in fact, it can transform a cost into a benefit, a waste product into a resource. In this way it becomes possible to create a network, i.e. a system that can feed and support itself, of companies (and producers) that can exchange resources and competencies with consequent gain for all the operators involved in the network of relationships (Fig. 3).

Determining new uses for the outputs that still exist locally reinforces the link between the local companies, increases their earnings, and results in a new and significant impact on the local community. The contribution of systemic design to the valorization and protection of the territory is therefore vital. By using the territory and resources we advance a kind of development that gives priority to the local community and allows the creation of ecological productive networks.

The induced links between companies minimize the use of external resources, allow more clarity on the traceability of the industries involved and help determine strategies for potential additional tools for local development. The network offers concrete possibilities to transform waste into materials worthy of appropriate, rational and targeted management, and more importantly, profitable reuse: this reinforces the concept according to which an efficacious protection of the environment is not in conflict with the economic growth of businesses. The greatest innovation offered by this methodology consists of raising the awareness of producers

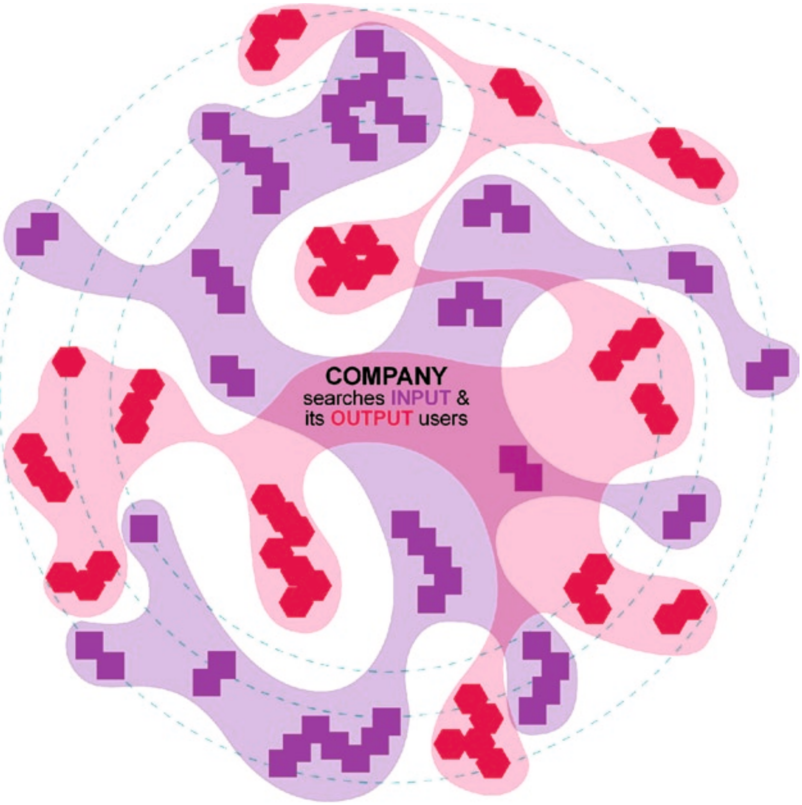

Fig. 3 Ecological productive network: new connections are created between different productive fields

that the problem of waste can be solved by activating complex relations in which the outputs of one productive process connect the nodes, which are local companies, of a network in which know-how, well-being, material and energy transit.

It creates the context for a set of links between energies and materials, productive systems that are self-sufficient in terms of energy, production and procurement. The safeguard of territorial biodiversity and the development of local resources, favored by a systemic approach lead to the generation of a balanced social and economic system that relates to people's needs for well-being according to the rhythms of natural cycles.

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Transgenic Bt Corn Hybrids and Pest Management in the USA

Siddharth Tiwari and Roger R. Youngman

Abstract Corn, *Zea mays* L., grown in many areas of the United States suffers from a variety of insect species that attack virtually all parts of the growing plant. Many conventional pest management programs have been developed to combat these insects with varying degrees of success. In the mid-1990s, the commercial introduction and subsequent widespread adoption of Bt transgenic hybrids has all but transformed conventional corn pest management programs. The initial target of Bt corn, which contains insecticidal protein encoding genes from *Bacillus thuringiensis* (Bt), were stalk boring insects, such as the European and southwestern corn borers. Within a few years of the introduction of Bt hybrids for stalk boring insects, Bt hybrids targeting western and northern corn rootworms were introduced. Since their introduction, however, Bt corn hybrids have come under considerable scrutiny. They have been reported to produce higher yields as well as lower pesticide exposure to humans, non-target organisms, and the environment. Questions, however, have been raised on such issues as contamination of the food chain, resistance development, the overall sustainability of the technology, and more recently, the high costs of Bt hybrids relative to non-Bt hybrids. The present chapter delves into some of the issues and challenges surrounding the continued use of Bt corn hybrids and the strategies employed to address such issues.

Keywords *Bacillus thuringiensis* • Field corn • IPM • Transgenic corn• *Zea mays*

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1 Introduction

Corn, *Zea mays* L., is one of the world's most important crops, with the total production of more than 791 million metric tons in 2007–2008 (USDA 2009a). The United States (U.S.) ranks first among corn growing nations, with a production of over 331 million metric tons in 2007–2008, which is about 42% to the total corn production in the world (USDA 2009).

Considering the economic importance of this crop throughout the world and the U.S., insect pests associated with this crop have received a considerable amount of attention among researchers, growers, policy makers and industry. In North America, about 90 insect pests are found to be associated with this crop (Steffey et al. 1999); however, only a few are considered economically important. Economically important pests of corn can be broadly divided into two groups on the basis of their feeding patterns and plant parts where damage occurs: stalk-tunneling and root-feeding. Among the stalk-tunneling insects, European corn borer, *Ostrinia nubilalis* (Hübner), (Lepidoptera: Crambidae), and southwestern corn borer, *Diatraea grandiosella* Dyar, (Lepidoptera: Crambidae) (Metcalf and Metcalf 1993; Mason et al. 1996; Calvin and Van Duyn 1999; Knutson and Davis 1999; Tiwari et al. 2005a, b) are the most important.

The major root-feeding insects on corn are the northern corn rootworm, *Diabrotica barberi* Smith and Lawrence, western corn rootworm, *D. virgifera virgifera* LeConte, and Mexican corn rootworm, *D. virgifera zeae* Krysan and Smith (Coleoptera: Chrysomelidae) (Branson et al. 1982; Levine and Oloumi-Sadeghi 1991). In addition, there are secondary soil insects, which include several species of wireworms (Coleoptera: Elateridae), seedcorn maggot (Diptera: Anthomyiidae), annual white grubs (Coleoptera: Scarabaeidae), and true white grubs (Coleoptera: Scarabaeidae). Depending on the particular species, they can be found feeding on the roots or other belowground parts of the plant (Hunt and Baker 1982; Youngman et al. 1993; Keaster and Riley 1999; Eckenrode and Webb 1999; McLeod et al. 1999; Tiwari et al. 2005a, b).

Historically, management of insect pests in corn has focused on cultural and conventional chemical control programs (Hyde et al. 2000). However, over the past decade, pest management programs for economically important insects have changed dramatically with the commercial availability of *Bacillus thuringiensis* transgenic corn hybrids (Bt hybrids). Under some conditions, pest management programs targeting economically important insects have been reduced to simply planting Bt hybrids. However, some growers choose not to plant Bt hybrids in areas where historically low pest pressures occur. Instead, growers rely on such practices as crop rotation, application of conventional insecticides, and asynchrony between crop susceptibility and pest infestation.

In 2004, adoption of Bt hybrids led to a 10.57 million kilogram reduction in the use of pesticides (Drury et al. 2008), thereby reducing the environmental impact associated with pesticide use and greenhouse gas emissions (Brookes and Barfoot 2008). In addition, Bt hybrids have played a role in increasing net economic benefits at the farm level (Brookes and Barfoot 2008). Other advantages of planting Bt hybrids include: less need for scouting (Obrycki et al. 2001; Crowder et al. 2006), protection against lepidopteran pests extending to storage (Giles et al. 2000), and lower levels of fungal pathogens and mycotoxins in the absence of stalk borer damage (Munkvold et al. 1999). However, planting Bt hybrids has raised concerns, such as increased cost input (Hyde et al. 1999), resistance development (Obrycki et al. 2001) and effects of Bt toxins on non-target organisms (Hilbeck et al. 1998; Höss et al. 2008; Prihoda and Coats 2008). Efforts have been made to address the aforementioned concerns using scientific research and regulatory approaches. Studies have reported that planting Bt hybrids result in higher returns than non-Bt hybrids under the following conditions: high pest pressure and late plantings (Hyde et al. 1999; Pilcher and Rice 2003; Wolf and Vogeli 2009).

The issue of insect resistance development to Bt toxins has been addressed by the United States Environmental Protection Agency's (USEPA) mandated Insect Resistance Management (IRM) plan. An IRM plan for Bt transgenic corn requires that a specified percentage of acreage be planted with a regular, non-transgenic corn hybrid. If above threshold levels of target pests are found in the non-Bt hybrid refuge, they can be managed with conventional management programs. Studies on the non-target effects of Bt toxins have yielded inconsistent results among the different taxonomic classes of non-target organisms (Hansen and Obrycki 2000; Höss et al. 2008).

2 Insect Pests of Corn

For the purpose of this chapter, we will focus our discussion on insect pests that are directly or indirectly impacted by currently available Bt hybrids.

2.1 Stalk Tunneling and Leaf/Ear Feeding Insects

Among stalk tunneling insects, European corn borer, *Ostrinia nubilalis* (Hübner), (Lepidoptera: Crambidae) (Mason et al. 1996; Calvin and Van Duyn 1999), and southwestern corn borer, *Diatraea grandiosella* Dyar, (Lepidoptera: Crambidae) (Metcalf and Metcalf 1993; Knutson and Davis 1999) are among the most important pests that occur throughout most of the corn growing areas of the U.S. Crop losses and management costs for European corn borer are reported to exceed $1 billion annually in the U.S. (Mason et al. 1996). Annual losses from southwestern corn borer are estimated at several million dollars (Morrison et al. 1977). In some corn growing areas, common stalk borer, *Papaipema nebris* Guenée, (Lepidoptera: Noctuidae) is also considered as an occasional pest (Solomon 1988) (Figs. 1 and 2).

The first and second instars of European corn borer feed on leaves in whorl-stage corn causing a shothole-like appearance. The late third instar starts tunneling into the stalks, ears, or ear shanks, with the majority of larvae having bored into the stalks by the fourth instar (Fig. 3). The southwestern corn borer causes injury similar to

Fig. 1 Mature larva of the common stalk borer, *Papaipema nebris*, boring into a corn plant early in the growing season. Feeding within the stalk causes deformed or stunted plants that often lead to the death of the plant

Fig. 2 Damage by common stalk borer larvae resulting in the stunted and abnormal growth of corn plants. Severe damage to the central part of the plant results in the death of central whorl. This condition has been referred as ‘dead heart’

Fig. 3 Stalk tunneling by late third and later instars of European corn borer, *Ostrinia nubilalis*, in field corn. Similar tunneling can also be seen in ears or ear shanks

European corn borer, except for one major difference. The mature larva girdles the stalk at the base just above the soil surface late in the season. This late season girdling often results in severe stalk lodging during harvest or from high winds (Knutson and Davis 1999). The southwestern corn borer larva overwinters in a cell, it has made at the base of stalk just below the soil surface (Knutson and Davis 1999).

Other insect pests that feed on corn leaves or the ear include fall armyworm, *Spodoptera frugiperda* (J. E. Smith) and corn earworm, *Helicoverpa zea* (Boddie). Of these, fall armyworm is of greater economic importance (Buntin et al. 2001). Both pests are found during the whorl stage; however, injury also continues to later stages (Buntin et al. 2001). Unlike the corn earworm, which restricts feeding to the ear tips, the fall armyworm is capable of causing severe leaf and kernel damage late in the season (Archer and Bynum 1998).

2.2 *Seed and Root Feeding Insects*

As mentioned previously, the major root-feeding insects on corn are the northern corn rootworm, western corn rootworm, and Mexican corn rootworm. Crop losses and management costs attributed to corn rootworms have been estimated to cost U.S. growers over $1 billion annually (Rice 2004). This estimate is now considered to be an underestimate since a soybean variant of the western cornworm has evolved resistance to crop rotation in the central U.S. corn belt (Gray et al. 2009).

Feeding injury on corn roots begins with the first instar. Early instars feed on root hairs and outer root tissue, while older instars burrow and feed in the inner root core.

Fig. 4 Developmental stages of Japanese beetle, *Popillia japonica*. Larval stage of Japanese beetle referred as white grubs (**a**) causes injury during early season by chewing off the fine rootlets of corn plants. This causes wilting and purpling of the stem. Grubs continue to feed until late May or early June when they pupate in an earthen cell (**b** shows prepupal stage) about 1 – 3 inches deep in the soil. Adults (**c**) feed on corn silks which interfere with pollination resulting into impaired kernel development and grain yield

Heavy infestation by corn rootworms can seriously weaken the root system, impeding the transport of water and nutrients from the roots to aboveground plant parts, as well as lead to stalk lodging (Chiang 1973; Levine and Oloumi-Sadeghi 1991; Tollefson and Levine 1999; Sutter 1999). After feeding for several weeks, the third instar pupates in a small earthen cell. Adults are active from mid- to late-summer, during which time they mate, feed on corn silk, pollen, and kernels of exposed ear tips (Youngman and Tiwari 2004).

In addition, numerous species of secondary soil insects are considered sporadic pests of germinating corn seeds or early stage corn (Hunt and Baker 1982; Youngman et al. 1993; Keaster and Riley 1999; Eckenrode and Webb 1999; McLeod et al. 1999; Tiwari et al. 2005a, b). Important secondary soil insects include several species of 'annual' and 'true' white grubs (Fig. 4) (Coleoptera: Scarabaeidae), wireworms (Coleoptera: Elateridae), and seedcorn maggot (Diptera: Anthomyiidae). Damage caused from wireworms, annual white grubs, and seedcorn maggot is primarily due to feeding on the germinating corn seed and emerging roots (Youngman et al. 1993). Damage caused by true white grubs is primarily restricted to the developing corn roots (Hunt and Baker 1982; McLeod et al. 1999).

3 *Bacillus Thuringiensis* (Bt)

Bacillus thuringiensis is a rod-shaped, gram positive, spore forming bacterium that is isolated from various habitats worldwide (Schnepf et al. 1998). *B. thuringiensis* produces a proteinaceous parasporal crystalline inclusion body formed within the bacteria during sporulation (Gill et al. 1992). The crystalline inclusion body contains from one to several δ-endotoxins that are responsible for causing death in certain species of insects, yet are harmless to humans and most non-target insects.

Current classification of Bt toxins is based on the nomenclature system developed by Crickmore et al. (1998). This nomenclature assigns a name to each holotype sequence based on the degree of evolutionary divergence as estimated by phylogenetic tree algorithms. Currently 204 holotype sequences for insecticidal proteins have been identified in various strains of *B. thuringiensis*, of which 195 are Cry and nine are Cyt δ-endotoxins (Crickmore et al. 2010). Based on holotype sequences, Cry endotoxins are currently divided into 60 families (from Cry1 to Cry60) and Cyt endotoxins are divided into two families (from Cyt1 to Cyt2) (Crickmore et al. 2010).

3.1 Mode of Action of B. Thuringiensis

The insecticidal activity of *B. thuringiensis* occurs after a susceptible insect ingests the crystalline inclusion body. After reaching the midgut, the ingested crystalline inclusion body is solubilized by the alkaline environment and enzymatic proteases, resulting in the release of one or more δ-endotoxins (Lambert and Peferoen 1992; Gill et al. 1992; Schnepf et al. 1998; Moellenbeck et al. 2001; Ferré and Van Rie 2002; Whalon and Wingerd 2003). Trypsin-like or chymotrypsin-like proteases in the insect gut start acting on the released endotoxins and continue to act until a trypsin resistant core protein is reached (55–75 kDa) (Schnepf et al. 1998; Moellenbeck et al. 2001; Ferré et al. 2008). This is followed by the protease-resistant core protein passing through the peritrophic membrane and binding to specific receptor (membrane protein complex) on the apical brush border of midgut columnar cells. This binding results in pore formation, cell swelling, cell lysis and ultimately insect death. Binding between the protease-resistant core protein and receptors on midgut columnar cells is highly species specific, so insects lacking the specific receptors are not harmed (Dorsch et al. 2002). Failure or reduction of the protease-resistant core protein to bind with a specific receptor on the apical brush border of the midgut columnar cells is one of the mechanisms of resistance development (Ferré and van Rie 2002).

3.2 Bt Hybrids

The first transgenic corn hybrid containing a modified short sequence of genes from *B. thuringiensis* against an insect pest was registered by the USEPA in 1995 (Shelton et al. 2002) under the names of "KnockOut®" (Syngenta Seeds [formerly Novartis Seeds]) and "NatureGard®" (Mycogen Seeds). Both hybrids contain event 176, Cry1Ab endotoxin, for European corn borer and other Lepidoptera pests. However, Bt hybrids with event 176 are no longer registered (Glaser and Matten 2003). In 1996, Bt hybrids containing event Bt11 under the name of "Agrisure™ CB" by Northrup King, and event Mon810 under the name of "YieldGard®" by Monsanto were commercially released; both events encoded the Cry1Ab endotoxin. In the years following, the USEPA registered two more Bt events for use in corn (Youngman and Tiwari 2004): event TC 1507 in 2001 developed jointly by Pioneer/Dupont and Dow AgroSciences under the name "Herculex™ I *Insect Protection*" and event Mon863 in 2003 developed by Monsanto under the name "YieldGard® Rootworm". Event TC 1507, Cry1F endotoxin, targeted black cutworm, fall armyworm, and European corn borer, and event Mon863, Cry3Bb, targeted corn rootworms.

The USEPA has since registered stacked Bt hybrids designed to control two different types of insects, such as "YieldGard® Plus" (Monsanto) in October 2003, and "Herculex® XTRA *Insect Protection*" (Dow AgroSciences and Pioneer Hi-Bred International) in October 2005. YieldGard® Plus contain events Mon 810 and Mon 863, encoding for Cry1Ab1 and Cry3Bb1 endotoxins, respectively (USEPA 2005a). Herculex™ XTRA *Insect Protection* contains event DAS-59122-7 encoding for Cry34Ab1 and Cry35Ab1 endotoxins, and event TC1507 encoding for Cry1F endotoxin (USEPA 2005b). Cry34Ab1 (14 kDa) and Cry35Ab1 (44 kDa) endotoxins are a relatively new class of insecticidal proteins identified from a *B. thuringiensis* strain PS149B1 that acts against corn rootworms (Herman et al. 2002; Gao et al. 2004). In October 2006, the USEPA registered Agrisure™ RW Rootworm-Protected Corn (Syngenta Seeds). Agrisure™ RW Rootworm-Protected Corn contains event MIR604, which produces a modified Cry3A (mCry3A) endotoxin (USEPA 2006). The modified Cry3A gene, recreated from *B. thuringiensis* subsp. *tenebrionis,* with its optimized expression in corn claims to have enhanced activity against larvae of the western corn rootworm and northern corn rootworm (USEPA 2006). In 2007, the USEPA registered Agrisure™ CB/RW (Syngenta Seeds) as another stacked hybrid conatining events Bt11 and MIR604 expressing Cry1Ab and mCry3A endotoxins, respectively (USEPA 2008). The most recent addition to the list is SmartStax™ (Monsanto and Dow AgroSciences) as another stacked hybrid containing events MON 89034, TC1507, MON 88017 and DAS-59122-7 expressing Cry1A.105 and Cry2Ab2; Cry1F; Cry3Bb1; and Cry34Ab1 and Cry35Ab1 endotoxins, respectively (USEPA 2009). According to Ostlie et al. (1997), Bt hybrids exhibit different levels of protection, depending on the type of genetic event and promoter used in developing a hybrid. The genetic event, in addition to a promoter, affects the amount, type, and location of the production of the endotoxin in the plant. For example, Bt hybrids with events Bt11 and Mon810 provide protection against first and second generation European corn borer larvae. Bt hybrids containing event 176 provide less acceptable protection against second generation larvae. As Ostlie et al. (1997) pointed out; events Mon810 and Bt11 express the Cry1Ab endotoxin in all plant tissues with the exception of root tissues, whereas event 176 expresses endotoxin only in green tissue and pollen. In addition, Ostlie et al. (1997) noted that Bt hybrids with events Bt11 and Mon810 provided 93% control of southwestern corn borer, whereas Bt hybrids with event 176 provided only 19% control of this pest.

Bt hybrids containing event Mon863 continue to produce endotoxins throughout the plant (Vaughn et al. 2005). In a laboratory study conducted by Vaughn et al. (2005), Bt hybrids containing event Mon863 (encoding for Cry3Bb1 endotoxin) exhibited a declining trend in root expression of Cry3Bb1 endotoxin from the V4 to V9 growth stage; however, this declining trend had no negative effect on corn roots despite rootworm pressure. In a study cited by Rice (2004), YieldGard® Rootworm (event Mon863) and YieldGard® Plus (stacked hybrid) (events Mon 810 and Mon 863) were tested against the soil insecticide terbufos (Counter 20CR) and several non-Bt hybrids in protecting corn roots from damage caused by corn rootworms. The study showed that the Bt hybrids were 100% consistent in protecting corn roots from economic damage, whereas Counter 20CR was only 63% consistent. Moreover, little or no protection from corn rootworm feeding was detected in the non-Bt hybrids.

4 Insect Resistance Management

Adoption of Bt corn hybrids worldwide has increased tremendously since the first commercial release in 1995. In 2009, 85% of the corn acreage in the U.S. was under Bt hybrids; this includes all the available transgenic Bt hybrids (USDA 2009b)

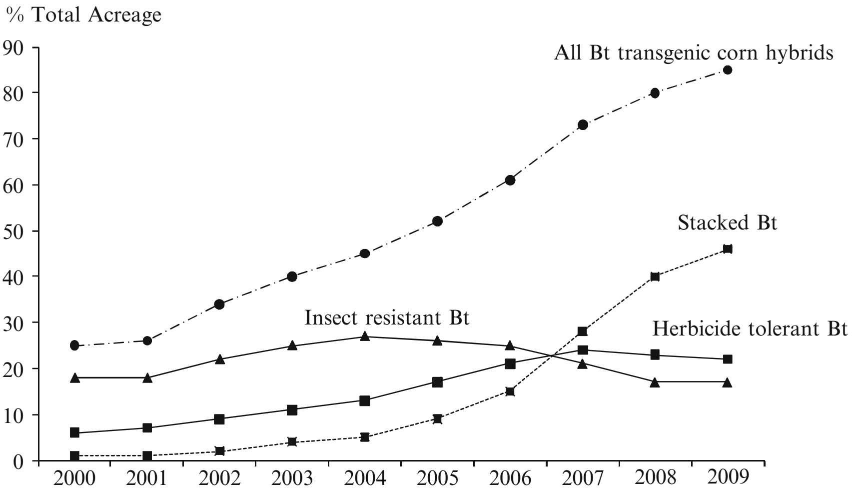

Fig. 5 Increase in the acreage under Bt corn hybrids from 2000 to 2009 in the United States. The acreage under Bt corn hybrids has been continuously increasing since the first commercial release of Bt hybrids in 1995. Bt corn hybrids are genetically modified corn hybrids containing a modified short sequence of genes from a bacterium, *Bacillus thuringiensis*. These genetically modified hybrids produce toxins in the host plant that are targeted against specific insect pests.
Source: http://www.ers.usda.gov/Data/BiotechCrops/alltables.xls, accessed April 12, 2010

(Fig. 5). The increased acreage under Bt hybrids has benefited growers in several ways, such as fewer applications of insecticides, higher yields and less exposure to humans and environment from insecticides. However, it has presented some new challenges. One of the most important challenges presented by the increasing acreage under Bt hybrids is the risk of developing resistance to Bt expression in the target insects (Gould 1998; Zhao et al. 2003). Scientists, pest management practitioners, and environmental regulators have responded to this challenge by developing insect resistance management strategies (IRM) for the purpose of delaying development of resistance to Bt events in the target pests (Hyde et al. 2000; Glaser and Matten 2003; Zhao et al. 2003; Bates et al. 2005; Bourguet et al. 2005). Considering the importance of this issue, the USEPA mandated that all companies registering Bt hybrids develop and deploy IRM strategies to delay the development of resistance in target pests.

During the early stages of developing IRM strategies, several tactics were designed and developed (Roush 1997). One strategy is the planting of Bt hybrids, which express moderate levels of toxin to delay the development of resistance in the target pest (Bates et al. 2005). The idea behind using a moderate level of toxin was to maintain survival of a susceptible proportion of the population. Another tactic to mitigate resistance development is planting Bt hybrids expressing a high level of toxin (high-dose strategy) (Zhao et al. 2003). The idea being that the expression of endotoxin is high enough to kill any heterozygous resistant larvae, which would otherwise survive and reproduce. Planting Bt hybrids expressing a high level of toxin in addition to planting a non-Bt refuge has become the primary element of IRM strategies (Dalecky et al. 2006; Tabashnik 2008; USEPA 2005a, b). A Scientific Advisory Panel Subpanel to FIFRA defined high dose as "25 times the toxin concentration needed to kill susceptible larvae" (USEPA 1998). The Subpanel also defined structured refuges to "include all suitable non-Bt host plants for a targeted insect that are planted and managed by people". However, Bt hybrids containing the event Mon863, which produces Cry3Bb endotoxin that targets corn rootworms, as well as other Bt hybrids targeting corn rootworms are reported to express low-moderate levels of toxin (Siegfried et al. 2005; Vaughn et al. 2005; Meihls et al. 2008).

4.1 High-Dose Toxin and Refuge Strategy for Single Event Bt Hybrids against Corn Borers

This strategy involves two components: planting Bt corn hybrids, which express a high dose of toxin; and refuge planting of non-Bt corn hybrids. This strategy has shown to be an effective way of delaying the development of resistance to Bt toxins (Alstad and Andow 1995; Gould 1998; Zhao et al. 2003; Bates et al. 2005; Dalecky et al. 2006; Eizaguirre et al. 2006). Under this strategy, the Cry1Ab toxin produced by Bt hybrids is high enough to kill all susceptible homozygous, and most of the resistant heterozygous target pests. The few resistant heterozygous individuals remaining will most likely breed with susceptible homozygous individuals from refuge areas. The effect of which being a greatly diminished production of resistant heterozygous individuals in subsequent populations (Gould 1998; Vacher et al. 2003; Bourguet et al. 2005). Another advantage of the high-dose toxin approach is maintaining host plant damage below the economic threshold (Bates et al. 2005). The USEPA has mandated various plans on the size and layout of refuge planting based on agronomic conditions and the target pest (USEPA 2001; USEPA 2005a, b) (Fig. 6).

According to the USEPA requirements, refuge area requirements for Bt hybrids targeting European corn borer, southwestern corn borer, and other lepidopteran pests has been divided into two categories: non-cotton growing areas and cotton growing areas (Youngman and Tiwari 2004). The USEPA requirements state that growers in non-cotton growing areas may plant up to 80% of their corn hectares using a Bt hybrid, with the remaining 20% serving as the refuge (USEPA 2000). In cotton growing areas, growers may plant up to 50% of their corn hectares using a Bt hybrid, with the remaining 50% serving as the refuge (USEPA 2000). The large percentage of refuge in cotton areas was recommended to prevent resistance development in corn earworm populations (Gould et al. 2002) given that corn is a major host source for corn earworm development in the mid-Atlantic.

A refuge may be located within, adjacent, or up to 0.8 km (0.5 mile) from the Bt hybrid field. Distance of refuge from the Bt hybrid field is based on information on insect flight and oviposition behavior (Glaser and Matten 2003). The purpose of which is to promote random mating between susceptible moths from refuge areas

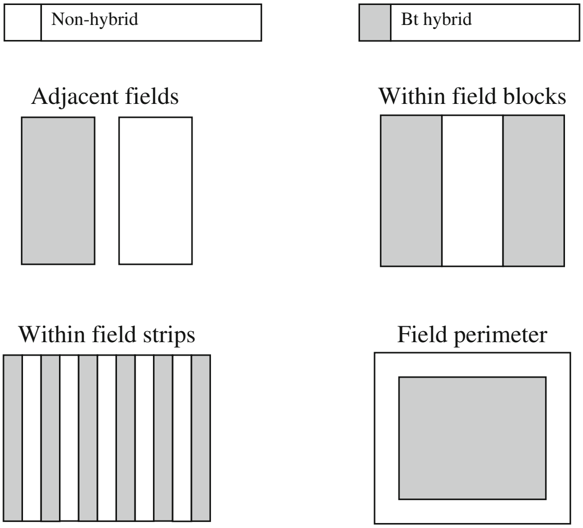

Fig. 6 Different layouts of non-Bt refuge and Bt corn hybrid plantings for insect resistance management. The United States Environmental Protection Agency has mandated various plans on the size and layout of refuge planting by non-Bt corn hybrids to delay the development of resistance against Bt toxins

with resistant survivors from Bt hybrid fields. A refuge up to 0.8 km (0.5 mile) away from the Bt hybrid field must not be treated with any insecticides for corn borers. If the refuge is to be treated for corn borers, it must be within 0.4 km (0.25 mile) of the Bt hybrid field. Also, sprayable formulations of Bt insecticides cannot be applied to the refuge. A refuge can be planted as strips (i.e., strips that are at least 6 and preferably 12 adjacent rows wide) within the Bt hybrid field, or as blocks within, adjacent, or away from the Bt hybrid field. A minimum of six rows was based on a simulation modeling of insect movement and mating (Onstad and Guse 1999). In addition, a refuge can be planted as a field perimeter or as end rows (Fig. 4). Mixing seeds of Bt hybrids and non-Bt hybrids is not recommended for managing corn borers (Youngman and Tiwari 2004).

4.2 Moderate-Dose Toxin and Refuge Strategy for Single Event Bt Hybrids against Corn Rootworms

The IRM strategy for Bt hybrids targeting corn rootworms is similar to the IRM strategy for Bt hybrids targeting European corn borer and other lepidopterans (Youngman and Tiwari 2004). According to Gray (2001), an IRM strategy involving numerous within-field refuge strips would be more effective than separate block refuges in the case of Bt hybrids targeting corn rootworms. Gray (2001) noted that pre-mating dispersal of adult corn rootworms away from their field of emergence is very limited compared with European corn borer where mating occurs in tall grass outside of cornfields, with subsequent egg laying occurring randomly across the landscape.

In certain areas of the Midwest Corn Belt, where crop rotation as a cultural control option is no longer effective against larvae of western and northern corn rootworms, it has been recommended to use a refuge for first-year corn if a Bt corn rootworm hybrid targeting corn rootworms is planted. Western corn rootworm has adapted to crop rotation by switching from corn to soybean to lay eggs (Gray et al. 1998; Rondon and Gray 2004). Northern corn rootworm has adapated to crop rotation by extending egg diapause from one to two years (Krysan et al. 1984; Levine et al. 1992; Gray et al. 1998). In both cases, planting a Bt corn rootworm hybrid is recommended as one of the best ways to manage the rotation resistant problem associated with corn rootworms (Onstad et al. 2003).

4.3 Refuge Planting for Stacked Bt Hybrid against Corn Borers and Corn Rootworms

According to the USEPA, refuge area requirements for stacked Bt hybrids targeting corn borers and corn rootworms have been divided into two categories: non-cotton growing areas and cotton growing areas (USEPA 2005a, b). USEPA requirements state that growers in non-cotton growing areas may plant up to 80% of their corn hectares using a Bt hybrid targeting corn borers, with the remaining 20% serving as the refuge (USEPA 2005a, b). However, in cotton growing areas, growers may only plant up to 50% of their corn hectares using a Bt hybrid targeting corn borers, with the remaining 50% serving as the refuge (USEPA 2005a, b). The refuge may be planted in two ways: either as a common refuge for both corn borers and corn rootworms or as separate refuges for corn borers and corn rootworms (USEPA 2005a, b).

The common refuge involves planting corn hybrids that do not contain Bt events for either corn borers or corn rootworms. The refuge area must represent at least 20% (in non-cotton growing areas) and 50% (in cotton growing areas) of a grower's corn hectares (i.e., sum of stacked Bt hybrid hectares and refuge hectares). The refuge can be planted as a block, perimeter strips, or in-field strips. If perimeter or in-field strips are planted, the strips must be at least six, and preferably 12 adjacent rows wide. The common refuge can be treated with a soil-applied or seed-applied insecticide to control rootworm larvae and other soil pests. In addition, the refuge may be treated with a non-Bt foliar insecticide for control of late season pests if pest pressure reaches an economic threshold; however, if corn rootworm adults are present at the time when foliar applications are made then the stacked Bt hybrid acres must be treated in a similar manner.

The second option is planting separate refuge areas for corn borers and corn rootworms. A corn borer refuge involves planting corn hybrids that do not contain Bt events for corn borers on at least 20% of the hectares in non-cotton growing areas, and on at least 50% of the hectares in cotton growing areas. These refuge areas are based on the total corn hectares a grower plants each season (i.e., the sum of stacked Bt corn hybrid hectares and corn borer refuge hectares), and must be planted within 0.8 km (0.5 mile) mile of the stacked Bt hybrid field. The corn borer refuge can be treated with a soil-applied or seed-applied insecticide for corn rootworm larval control, or a non-Bt foliar-applied insecticide for corn borer control if pest pressure reaches an economic threshold.

A corn rootworm refuge involves planting corn hybrids that do not contain Bt events for corn rootworm, but can be planted with Bt corn borer hybrids. The corn rootworm refuge must represent at least 20% in non-cotton growing areas, and 50% in cotton growing areas. These refuge areas are based on the total corn hectares a grower plants each season, i.e., the sum of stacked Bt corn hybrid hectares and corn rootworm refuge hectares. The refuge can be planted as an adjacent block, perimeter strips, or in-field strips. The corn rootworm refuge can be treated with soil-applied or seed-applied insecticides to control rootworm larvae and other soil pests. The refuge can also be treated with a non-Bt foliar insecticide for control of late season pests; however, if rootworm adults are present at the time when foliar applications are made then the stacked Bt hybrid field must be treated in a similar manner.

4.4 Limitations with the High-Dose Toxin and Refuge Strategy

The high-dose toxin and refuge planting strategy for preventing resistance development in the target insect is based on three strict assumptions: inheritance of resistance is recessive in the target insect population (Liu et al. 2001), low presence of resistance alleles ($<10^{-3}$) in the target insect population (Roush and Miller 1986), and random or preferential mating between susceptible individuals from the refuge and resistant individuals from the Bt hybrid field (Vacher et al. 2003, Bates et al. 2005). However, there are examples where inheritance of resistance to Bt toxins is found to be incomplete or non-recessive, such as in a strain of *Helicoverpa armigera* to Cry1Ac toxin (Akhurst et al. 2003), *H. zea* to Cry1Ac toxin (Burd et al. 2003), and *O. nubilalis* to the Bt toxins in Dipel ES (Dipel ES contains Cry1Aa, Cry1Ab, CryIAc, Cry2A, and Cry2B endotoxins of *Bt*. Cry1Ab and Cry1Ac) (Huang et al. 1999). The idea behind the high-dose toxin refuge strategy is that it targets individuals with incompletely dominant resistance or heterozygous resistance (Bourguet et al. 2000). In a study conducted in 1997, strains of pink bollworm, *Pectinophora gossypiella,* collected from 10 Arizona cotton fields revealed that the estimated frequency of a major resistance allele to Cry1Ac toxin has increased to 0.16 (Tabashnik et al. 2000). In cotton, the variable developmental period found between resistant larvae of *P. gossypiella* on Bt transgenic cotton hybrids expressing Cry1Ac toxin and susceptible larvae on non-Bt transgenic cotton hybrids could lead to non-random mating between resistant and susceptible individuals (Liu et al. 2001). In a study on pre-copulatory dispersal and mating in *O. nubilalis*, it was found that females prefer mating near the emergence site before dispersal (Dalecky et al. 2006). In a similar study conducted by Bailey et al. (2007), they found that the mean (± SEM) distance flown by *O. nubilalis* adults was 5.05 ± 7.3 m in 12 h from the release site. This could be a limiting factor for random mating to take place between resistant and susceptible individuals. However, no significant violations have been reported to date with respect to target pests subjected to the high-dose refuge strategy (Bates et al. 2005; Tabashnik et al. 2008).

There are new issues facing the high-dose refuge strategy in terms of adhering to the physical limitations. Contamination of Bt hybrid seeds with non-Bt hybrid seeds as a result of off-types may promote more rapid development of resistance (Gould 1998; Bates et al. 2005). The movement of the target insect between Bt hybrids and other non-Bt host plants or weedy plants can lead to ingestion of intermediate doses of toxin by the target insect, which may eventually expedite the development of resistance (Gould 1998). In addition, pollen mediated gene flow from Bt hybrids to non-Bt hybrids (refuge) has been found to result in low to moderate levels of Bt toxin in refuge plants (Chilcutt and Tabashnik 2004).

5 Resistance Monitoring

Resistance monitoring has been an integral part of the IRM strategy to detect the development of resistance in target insects to Bt hybrid toxins. Several methods have been suggested for monitoring the development of resistance: annual damage reports by growers, direct monitoring of insect population susceptibility, dose–response bioassays, diagnostic/discriminating dose bioassays, F_2 screen, feeding disruption assays, and feral assays (Venette et al. 2000; Bourguet et al. 2005). However, the dose–response and diagnostic/discriminating dose bioassays are currently the most widely used methods (Bates et al. 2005; Bourguet et al. 2005; Huang 2006; Huang et al. 2007).

The dose–response bioassay as described by Bourguet et al. (2005) measures the change in EC_{50} and LC_{50} values in a natural population of the target pest over a period of time. This is done by exposing insects to a series of Bt toxin concentrations, and then using probit analysis to determine EC_{50} and LC_{50} values. The dose–response bioassay is more efficient in detecting high levels of resistance or resistance conferred by a dominant allele than in detecting early development of resistance conferred by a recessive allele (Bates et al. 2005; Huang et al. 2007). In addition, the dose–response bioassay can test large number of insects in a relatively efficient manner (Ferré et al. 2008).

The diagnostic/discriminating dose bioassay is based on the use of a single dose of a Bt toxin (i.e., the diagnostic/discriminating dose) (Huang 2006). The most commonly used diagnostic/discriminating dose is the LC_{99} value for susceptible strains, which is developed from a dose–response bioassay (Huang 2006). This single dose method is more efficient in detecting dominant resistance alleles or recessive resistance alleles at high levels (Huang et al. 2007). However, some of the limitations with the diagnostic/discriminating dose method are the need for a large sample size (Roush and Miller 1986) and decreased efficiency at detecting recessive alleles resistant to Bt toxins (Venette et al. (2000). Bourguet et al. (2005)) noted that this method is unlikely to detect early stages of resistance development.

Given that both the dose–response and diagnostic/discriminating dose bioassays are not suitable for detecting low levels of recessive alleles resistant to Bt toxins, suggestions have been made to integrate other resistance monitoring tools into the program. The F_2 screen and DNA marker methods are reported to have higher sensitivity for detecting low levels of recessive alleles resistant to Bt toxins (Huang 1997).

6 Role of Insecticides after Stacked Bt Hybrids

Following the commercial release of Bt hybrids for corn borers and corn rootworms, there has been a marked shift in the use of insecticides in corn production (Pilcher et al. 2002; Wilson et al. 2005; Brookes and Barfoot 2006). A multi-state survey was conducted over three years on corn grower use of insecticides to control European corn borer in the Midwest Corn Belt (Pilcher et al. 2002). Pilcher et al. (2002) reported that the percentage of growers that decreased their insecticide use has nearly doubled from 13.2% in 1996 to 26.0% in 1998. Rice (2004) estimated that planting Bt hybrids against corn rootworms will alone result in about a 75% reduction in insecticide use targeting corn rootworms. In a 2001 survey conducted among corn growers across five states, Wilson et al. (2005) reported that the perceived benefits of using Bt hybrids were reduced grower exposure to insecticides (69.9%) and lower levels of insecticide active ingredient in the environment (68.5%). At the national level, the planting of Bt hybrids has resulted in a reduction of insecticide active ingredient by 0.6 million kilogram and an annual environmental impact quotient (EIQ) by 21 million field EIQ/ha units from 1996 to 2005 (Brookes and Barfoot 2006). EIQ is calculated in terms of field value per hectare using various toxicological and environmental impact data for each pesticide (Kovach et al. 1992).

Although planting Bt hybrids has resulted in a significant reduction in the use of conventional insecticides on corn, it has not totally eliminated the use of insecticides in the majority of corn growing areas of the U.S. In fact, a high percentage of commercial Bt hybrids today come with insecticide-protected coated seeds, which are primarily treated with systemic neonicotinoids targeting secondary soil insects (Mullin et al. 2005; Magalhaes et al. 2007). In those situations where growers decide not to plant Bt hybrids, it is recommended that growers use pre-plant sampling methods to identify fields at risk to secondary soil insects (Keaster and Riley 1999, McLeod et al. 1999; Youngman et al. 1993). The most common methods for managing secondary soil insects are soil-applied insecticides or planting insecticide-protected coated seeds (Andersch and Schwarz 2003). The rate and type of insecticides used in either method depends on the target insect. Insecticides belonging to the organophosphate, carbamate, pyrethroid, or phenylpyrazole classes have been the most commonly used as soil-applied insecticides (Andersch and Schwarz 2003).

Due to several disadvantages associated with the conventional soil-applied insecticides (Altmann 2003; Andersch and Schwarz 2003), planting insecticide-protected coated seeds to manage early season secondary soil insects is now increasing and becoming more widely adopted. Imidacloprid, clothianidin, thiamethoxam and tefluthrin are the main insecticides used by seed companies to treat corn seeds for protection against early season feeding injury to germinating seeds and newly emerging roots (Mullin et al. 2005; Magalhaes et al. 2007).

With the widespread use of neonicotinoid seed protectants on Bt hybrid corn seeds, there is a growing concern for monitoring resistance development in insects that are the target of these seed protectants (Magalhaes et al. 2007), in addition to evaluating the indirect effects of neonicotinoids on non-target organisms (Mullin et al. 2005). Development of resistance to neonicotinoids has been documented in several insect species. Specific examples include whiteflies *Bemisia tabaci* (Gennadius) and *Trialeurodes vaporariorum* (Westwood), brown planthopper *Nilaparvata lugens* (Stal), Colorado potato beetle *Leptinotarsa decemlineata* (Say) and mango leafhopper *Idioscopus clypealis* (Lethierry) worldwide (Elbert et al. 2008). The development of resistance to neonicotinoids in adults and larvae of the Colorado potato beetle (Zhao et al. 2000; Nauen and Denholm 2005) raises two points for concern with respect to the continued, widespread use of neonicotinoid seed treatments on Bt corn rootworm hybrid seeds. First, the Colorado potato beetle and corn rootworms belong to the same taxonomic family (Chrysomelidae); and second, the Colorado potato beetle and corn rootworms share a similar history of developing resistance to insecticides in the major insecticide classes: chlorinated hydrocarbons, organophosphates, and carbamates. Although, in most cases, management of corn rootworm larvae is not intended through the use of neonicotinoid seed treatments where Bt corn rootworm hybrids are planted. Nevertheless, neonicotinoids still serve as an important tool for managing corn rootworms in refuge plantings and areas where growers choose not to plant Bt hybrids for corn rootworms.

A study was conducted to examine the effects of seed treatments associated with Bt hybrids expressing Cry3Bb1 and Cry1Ab/c endotoxins on several species of carabid beetles (Mullin et al. 2005). They found that adult beetles representing 16 carabid species, which had fed on the pollen of Bt corn hybrids suffered no significant toxicity, whereas beetles representing 18 carabid species suffered nearly complete mortality when exposed to corn seedlings grown from imidacloprid, thiamethoxam or clothianidin treated seeds.

In order to manage the increasing selection pressure from using seed treatment insecticides, Magalheas et al. (2007) provided a baseline tool for predicting and monitoring the early signs of resistance development among geographically distinct populations of western corn rootworm. High-dose and refuge strategy could be employed to delay resistance to neonicotinoids as suggested by Zhao et al. (2000) in their study reporting resistance development in *L. decemlineata* to imidacloprid. They reported that resistance to imidacloprid is an incompletely recessive trait. According to Elbert et al. (2005), efforts should be made to follow IRM guidelines for managing resistance development to neonicotionoid insecticides. The idea being to optimize the use of this technology against the target insects while simultaneously reducing their impact on non-target species.

7 Conclusion

Bt transgenic corn hybrids have become an integral part of corn production in most of the corn growing areas of the world (Bates et al. 2005; James 2008; Tabashnik 2008). Its continued adoption worldwide speaks of increasing confidence among corn growers for this technology. Higher returns from planting Bt hybrids as a result of increased yield and fewer insecticide applications (Pilcher et al. 2002; Wilson et al. 2005; Brookes and Barfoot 2006; James 2008) are the primary factors. Implementation of a robust IRM strategy, which is the first one of its kind to be implemented on such a large scale, further boosts the confidence of growers for the sustainable use of this technology. In addition, a regular monitoring plan for resistance development in the target pest is a necessary step against resistance development, the overall aim of which is to secure the long-term usefulness of the Bt technology. Implementation of these strategies has contributed much to the fact that no cases of failure in the Bt corn hybrid technology have been reported since its commercial introduction in 1995. In addition to Bt hybrids, the increasing trend in the use of insecticide-protected coated seeds, makes it imperative that IRM plans be developed and implemented for the target pests of this technology as well.

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Marker-Assisted Breeding in Higher Plants

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Abstract The deployment of DNA-based marker systems promises to accelerate the improvement of crop productivity worldwide. Numerous DNA fingerprinting assays, and more recently whole genome sequence information, have been utilized extensively for employing intrinsic genetic polymorphisms in the genomes of higher plants in phylogenetic studies, genetic mapping, and comparative genomic analysis. DNA markers set the stage for initiating genomic-based breeding strategies with several advantages over the phenotypic based selection procedures used in conventional breeding programs. In maize, successful applications have been exemplified by marker assisted introgression of novel genomic regions associated with anthesis-silking interval, marker-based diagnosis of plants containing the *opaque2* gene associated with quality, and marker-based prediction of hybrid vigor. New rice varieties are developed using DNA markers associated with genes and quantitative trait loci (QTLs) to provide resistance to both biotic stress, e.g. bacterial blight and blast, and abiotic stresses, and to improve yield and quality. A wheat variety 'Patwin' was developed through marker assisted selection for stripe and leaf rust resistance genes *Yr17* and *Lr37,* respectively. The stay-green trait conferring resistance to drought in sorghum has been explored at length. In tomato, cotton, potato, soybean and other crops, many genes conferring resistance against various biotic stresses have been incorporated from wild relatives using DNA markers. Wider adaptation of marker assisted breeding is limited by the narrow genetic base of elite gene pools for many plants. Multiple investigations reveal conservation of QTLs among some crop species, offering opportunities to gain information from one crop to improve others.

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Abbreviations

QTLs	Quantitative trait loci
QTN	Quantitative trait nucleotide
RFLP	Restriction fragment length polymorphism
PCR	Polymerase chain reaction
RAPD	Random amplified polymorphic DNA
SCAR	Sequence characterized amplified region
STS	Sequence tagged site
CAPS	Cleaved amplified polymorphic sequence
SSR	Simple sequence repeat
AFLP	Amplified fragment length polymorphism
SRAP	Sequence-related amplified polymorphism
SNPs	Single nucleotide polymorphisms
NILs	Near-isogenic lines
RILs	Recombinant inbred lines
DH	Doubled haploid
ILs	Introgression lines
BC	Backcross population
MAS	Marker assisted selection
MAB	Marker-assisted backcrossing
CPS	Conventional phenotypic selection
BB	Bacterial blight
CBB	Common bacterial blight
AB	Ascochyta blight
MSV	Maize streak virus
CLCuD	Cotton leaf curl disease
PSbMV	Pea seed-borne mosaic virus
TuYV	Turnip yellows virus
FW	Fusarium wilt
VW	Verticulum wilt
SDS	Sudden-death syndrome
ER	Extreme resistance
CMS	Cytoplasmic male sterility
OA	Osmotic adjustment

1 Introduction

Conventionally, plant breeders recombine traits present in different parental lines of cultivated and or wild species into single improved genotypes, through various breeding schemes. Multiple investigations illustrate that combination of complex characters encoded by multiple genes with additive effects and recessive genes, or pyramiding of small-effect genes influencing the same trait, are difficult to achieve through classical breeding methods (Beckmann and Soller 1986).

Recent developments in DNA marker approaches have brought a new dimension into the traditional area of plant breeding (Moose and Mumm 2008) through developing association between traits and genomic loci which pave the way for evolving new varieties in much less time (Xu and Crouch 2008). Polygenic traits that were previously difficult to analyze using conventional plant breeding methods, are now easily tagged by identifying tightly linked DNA markers. Marker-assisted selection (MAS) is a method of indirect selection of a trait by identifying the desired plants through such tightly linked DNA marker(s) (Ribaut and Hoisington 1998). DNA markers not only allow the easy and reliable identification of breeding lines, hybrids (Bastia et al. 2001), and cultivars (Mohanty et al. 2001), but also facilitate the monitoring of introgression from wild to elite cultivars (Paterson et al. 2003), assessment of genetic diversity and relatedness (Iqbal et al. 1997; Mukhtar et al. 2002; Rahman et al. 2002b, 2008b; Milligan 2003; Asif et al. 2006), gene pyramiding (Kuchel et al. 2005; Wang et al. 2007), genetic mapping (Mohan et al. 1997), analysis of quantitative trait loci (QTLs) (Paterson et al. 2003) and MAS (Ribaut and Hoisington 1998; Francia et al. 2005). DNA markers can provide means of detecting and resolving complications such as linkage drag (Young and Tanksley 1989), and suppression of recombination and segregation distortion (Jiang et al. 2000) which make DNA markers indispensable for crop improvement (Winter and Kahl 1995).

2 Benefits of Marker Assisted Selection

Marker-assisted breeding or marker aided selection can greatly enhance the efficiency and effectiveness of plant breeding relative to conventional methods. Once tightly linked molecular markers for a gene or QTL of interest have been identified (Collard et al. 2005), breeders can select true-to-type genotypes at an early stage of plant growth, avoiding the need to conduct large scale field trials. Plants with desirable traits that are difficult to evaluate in non-target environments (including the greenhouse), can be selected. Traits with low heritability can be selected with more accuracy. Pyramiding or combining of useful and multiple genes become much easier. Transfer of undesirable genes is avoided by reducing the chances of linkage drag, which is a serious problem during introgression of genes from wild species. Generally, the MAS procedure is time friendly and cost effective in developing crop varieties.

3 Pre-requisite for Marker Assisted Selection

A number of DNA fingerprinting assays (Semagn et al. 2006; Agarwal et al. 2008), such as restriction fragment length polymorphism (RFLP, Botstein et al. 1980), random amplified polymorphic DNA (RAPD, Williams et al. 1990), amplified fragment length polymorphism (AFLP, Vos et al. 1995), simple sequence repeats (SSRs, Tautz and Renz 1984) and single nucleotide polymorphism (SNPs, Collins et al. 1998) are now available for utilizing in MAS (Francia et al. 2004; Xu and Crouch 2008). Restriction fragment length polymorphism markers are reliable markers in linkage analysis and crop breeding, however, these are time consuming, expensive and require large amount of DNA for restriction and hybridization analysis (Paterson et al. 1993). RAPD is much faster and cheaper than RFLP analysis and uses only small amounts of DNA (Rahman et al. 2002b), but tend to be genotype-specific and can be difficult to reproduce in different labs. Microsatellites are extremely polymorphic, codominant in expression and generally robust. Amplified fragment length polymorphism is reliable and requires a minimum of a prior information (Vos et al. 1995), however, it is technically intricate and expensive. Single nucleotide polymorphisms are the most elemental DNA marker, directly reflecting nucleotide differences among genotypes, and are coming to be preferred over other marker systems as advances in DNA sequencing facilitate their discovery and utilization, because of their high occurrence in various genomes and codominance (Lindblad-Toh et al. 2000).

Besides cost, major limitations to the development of MAS might include limited understanding of genetic phenomena such as gene networks, epistasis, and genotype by environment interactions that complicate the relationship between genotype and phenotype. However with rapidly evolving marker technologies, the use of MAS approaches in crop improvement appears very promising (Ribaut and Betran 1999; Ribaut and Ragot 2007).

4 Utility of DNA Markers for Improving Crop Genomes

Different genes controlling agronomically important traits have been mapped and tagged with molecular markers which form the basis for initiating MAS (Francia et al. 2004) in different crop plants (Table 1 and 2). The large number of QTL mapping studies for diverse crop species have provided an abundance of DNA marker-trait associations, which have the potential to improve efficiency and precision of conventional plant breeding via marker-assisted selection (Collard and Mackill 2008). A comprehensive review of the application of MAS in molecular breeding programs would now be voluminous—in the following sections, a few examples are studied.

4.1 Family: Poaceae

4.1.1 Maize

Successful applications of MAS have been reported in maize (*Zea mays*) for introgressions of novel genes (Ragot et al. 1995), for diagnosing plants containing a single gene (*opaque2* gene associated with quality) (Dreher et al. 2003) and for improving

Table 1 Examples of successful application of marker assisted selection for crop improvement

Crops	Traits	DNA markers	Gene/locus	References
Maize	Hybrid performance	RFLPs[1]	QTLs	Stuber et al. 1999
	Yield and drought stress[a]	RFLPs, SSRs	QTLs	Ribaut et al. 1997; Bouchez et al. 2002; Ribaut & Ragot 2007; Blanc et al. 2008
	Insect resistance (*Diatraea* spp.)	RFLPs	QTLs	Bohn et al. 2001
	Maize streak virus (MSV) resistance[b]	SSRs	QTLs	Lagat et al. 2008
Rice	Bacterial blight (BB)[c]	STS, SSRs	*xa5*, *xa13* & *Xa21*	Singh et al. 2001; Sundaram et al. 2008
		SSRs, RFLPs	*Xa4, Xa25(t)*	Li et al. 2006
		STS, SSRs	*Xa7* and *Xa21*	Zhang et al. 2006
		SSRs	*xa13* and *Xa21*	Gopalakrishnan et al. 2008
	Blast resistance[d]	RFLPs	*Pi*1, *Piz*-5 and *Pi*ta	Hittalmani et al. 2000
	Yield and its components	RFLP, SSRs	QTLs	Septiningsih et al. 2003; Thomson et al. 2003
	Drought tolerance[e]	RFLP, SSRs	QTLs	Shen et al. 2001; Robin et al. 2003
	Cold tolerance[f]	SNP	OsAOX1a/Ctb_1, Ctb_2	Abe et al. 2002; Saito et al. 2004
	Salinity tolerance	RFLPs	QSNC-7, qSKC-1	Lin et al. 2004
	Grain quality	RFLPs, SSRs, AFLPs	Waxy gene	Zhou et al. 2003a
Wheat	Leaf rust[g]	SSRs	*Lr21, Lr34*	Huang and Gill 2001; Suenaga et al. 2003
		STS, SCAR, CAPS	*Lr1, Lr9, Lr24, Lr47*	Nocente et al. 2007
	Stripe and leaf rust	RFLPs, CAPS, SSRs	*Yr17, Yr18, Lr37, Sr38*	Helguera et al. 2003; Suenaga et al. 2003
	Yellow or stripe rust[h]	SSRs, STS	*Yr26*/*Xwe173* and *Xbarc181*	Wang et al. 2008
	Powdery mildew[i]	SRAP, STS, SSR	R genes/*Pm4a, Pm4b* and *Pm5e*	Huang et al. 2003; Ma et al. 2004; Yi et al. 2008
	Scab resistance[j]	SSRs	QTLs	Zhou et al. 2003b
	Al tolerance[k]	SSRs	Alt_{BH}	Nguyen et al. 2003
	Grain quality	PCR based	*Glu-B1x*	Xu et al. 2008a

(continued)

Table 1 (continued)

Crops	Traits	DNA markers	Gene/locus	References
Barley	Malting quality[l]	RFLPs	*Brz* and *Amy2*	Schmierer et al. 2005
	Frost tolerance	RAPDs, STS	QTLs	Toth et al. 2004
	Covered & loose smut	RAPD, SCAR and STS	*Ruhq, Run8*	Grewal et al. 2008
	Powdery mildew & leaf rust	SSRs	QTLs	Schmalenbach et al. 2008
	Al tolerance	SSRs	*Alp*	Raman et al. 2003
Sorghum	Stay-green[m]	RFLPs, SSRs, AFLPs	*Stg1–Stg4*	Sanchez et al. 2002; Harris et al. 2007
	Anthracnose	RAPD, SCAR, sequencing	$\mathrm{OPJ01}_{1437}$, SCJ01, contig_3966	Singh et al. 2006
	Cold tolerance	SSRs	QTLs	Knoll and Ejeta 2008
Cotton	Fiber quality[n]	SSRs, RAPDs	QTLFS1/QTLs	Zhang et al. 2003; Mumtaz 2007; Asif 2009; Chen et al. 2009
		SCAR	$\mathrm{SCAR431}_{1920}$	Guo et al. 2003
		RFLPs	QTLs	Chee et al. 2005a & b; Draye et al. 2005
	Bacterial blight[o]	AFLPs	QTLs	Jixiang et al. 2007
		RFLPs	QTLs for *Xcm*	Wright et al. 1998
	Fusarium wilt[p]	SSR	QTLs for *FWR*	Wang et al. 2009
	Cotton leaf curl disease[q]	RAPD, SSRs	$R_{1CLCuDhir}$, $R_{2CLCuDhir}$, $S_{CLCuDhir}$	Rahman 2002; Rahman et al. 2005a & b; Rahman et al. 2006; Rahman and Zafar 2007a, b
	Male fertility	RAPD, STS	Rf_1 and Rf_2	Zhang and Stewart 2004; Feng et al. 2005
	Leaf pubescence[r]	RFLPs	t_1–t_5	Wright et al. 1999
	Hairiness, nectariless, red leaf[r]	RAPD, SSRs	Linked loci	Rahman et al. 2002a; Rahman et al. 2003; Ali 2004
	Drought tolerance[s]	RFLPs	QTLs	Saranga et al. 2001; Paterson et al. 2003

Tomato	Soluble solids and fruit pH[t]	RFLPs, RAPD	QTLs, Brix9-2-5	Tanksley and Hewitt 1988; Frary et al. 2003; Lecomte et al. 2004
	Powdery mildew[u]	RFLPs, SCARs	*Ol-1* R gene	Huang et al. 2000
	Black mold[v]	RFLPs	QTLs	Robert et al. 2001
	Drought tolerance[w]	RFLPs	QTLs	Foolad et al. 2002
Potato	Late blight[x]	DNA markers	QTLs, R genes	Gebhardt & Valkonen 2001
	Virus resistance (PVY)[y]	RFLPs, CAPS, SSRs	Ry_{sto} gene	Song et al. 2005; Valkonen et al. 2008
	Verticillium wilt	CAPS	*Ve* gene	Bae et al. 2008
	Chip color[z]	DNA markers	sucrose synthase	Kawchuk et al. 2008
Soybean	Yield and its components[aa]	SSRs	QTLs, Sat_107, 4SP	Concibido et al. 2003; Wang et al. 2004; Zhu and Sun 2006; Charlson et al. 2009; Palomeque et al. 2009a, b
	Sudden-death syndrome (SDS)[ab]	RAPD, SSRs	Satt loci	Iqbal et al. 2001
	Root and stem rot[ac]	SSRs	*Rps3, Rps8*	Sandhu et al. 2005
	Soybean mosaic virus[ad]	ESTs	*Rsv*4	Hwang et al. 2006
	Southern root-knot nematode	SSRs, SNPs	SNP199, SNP358	Ha et al. 2007
	Insect resistance			
	Soybean aphid	SSRs	Satt435 & 463, *Rag1*	Li et al. 2007
	Seed quality[ae]	SSRs, SNPs	QTLs	Lightfoot 2008
Common beans	Common bacterial blight	SCAR, STS	CBB QTL, BC420	Fourie & Herselman 2002; Mutlu et al. 2005; Liu et al. 2008
	White mold	RAPD, AFLP	QTL	Ender et al. 2008
Peas	Powdery mildew resistance[af]	SCARs	*er1*, *er2* and *Er3*	Fondevilla et al. 2007 & 2008; Katoch et al. 2009
Chickpea	Ascochyta blight (AB)[ag]	SSR	QTLs	Santra et al. 2000; Taran et al. 2007; Anbessa et al. 2009

(continued)

Table 1 (continued)

Crops	Traits	DNA markers	Gene/locus	References
Brassica	Cytoplasmic male sterility (CMS) & fertility restorer	allele-specific PCR	*Rfo*	Hu et al. 2008
	Erucic acid contents	SNPs, SCARs	*Bn-FAE1.1*, *Bn-FAE1.2*	Rahman et al. 2008c
Cucumber	Yield and its components	RAPD, SCAR, AFLP, SNP, SSR	QTLs	Fazio et al. 2003a, b; Fan et al. 2006; Robbins and Staub 2009

QTLs quantitative trait loci, *RFLP* restriction fragment length polymorphism, *SSR* simple sequence repeat, *STS* sequence tagged site, *SNPs* single nucleotide polymorphisms, *AFLP* amplified fragment length polymorphism, *SCAR* sequence characterized amplified region, *CAPS* cleaved amplified polymorphic sequence, *SRAP* sequence-related amplified polymorphism, *RAPD* random amplified polymorphic DNA

[a] Drought stress causes ~15% losses in maize production annually. Reduction in anthesis interval period has positive association with yield under drought condition

[b] MSV disease has been reported only in Africa that is transmitted by small insects called leafhoppers

[c] Bacterial blight causes yield losses up to 50% worldwide

[d] Blast, a disease of fungal origin, depresses yield production between 10% and 30%

[e] QTLs for root length and osmotic adjustment have positive impact on drought tolerance in rice

[f] Cold stress in rice is responsible for ~30–40% yield reduction in temperate regions of the rice growing areas of the world

[g] Leaf rust usually causes 1% to 20% yield losses

[h] Stripe rust can cause yield losses up to 25% if the weather is conducive

[i] It is a fungal disease which can cause 40% reduction in yield. More than 30 resistance genes have been reported

[j] It is also a fugal disease which infects the open flowers, and the diseased spikelets become a bleached, light-straw color and ripen prematurely

[k] Generally the members of the family *Poaceae* are sensitive to aluminum salt found in acidic soils. Tolerance to Al is controlled by a major gene mapped on the long arm of Chr 4D

[l] Malting is a process in which grains are allowed to germinate and then immediately air/heat dried. Presently, malt extract is ~82% while breeders need to surpass the upper limit of 85% for which breeding efforts are underway

[m] Stay-green, controlled by four QTLs, confers drought tolerance through maintaining green stems and upper leaves under limited water supply

[n] Fiber length, finess, strength, maturity etc. are the most important quality features

[o] Bacterial blight is seed and trash borne. Resistance to the disease is controlled by more than ten genes

[p] Fusarium wilt is a major vascular root disease of cotton. Typical symptoms are yellowing, wilting and defoliation of the plant which ultimately lead to death

[q] Typical symptoms of the disease are leaf curling, darkened veins, vein swelling and enations on the undersides of leaves that develop into cup-shaped, leaf like structures. Resistance to the disease is controlled by two major resistant genes and a suppressor gene

[r] These traits buffer against the spread of insect pests

[s] Osmotic adjustment and high net photosynthetic rate under drought are being used as a screening criterion

[t] These are the traits which determine the quality of tomato fruit, and were introgressed in cultivated tomato species (*L. esculemtum*) from wild species (*L. chmielewskii*)

[u] Powdery mildew is caused by a fungus *Oidium lycopersicum.* Typical initial symptoms are light green to yellow spots appear on upper surface of the leaf

[v] The disease is caused by *Alternaria alternate* which affects ripe fruit. Resistance genes have been introgressed from wild tomato in to the cultivated species

[w] It affects at seed germination and early seedling growth

[x] It usually forms lesions on leaves, stems and tubers

[y] It is the disease of viral origin which is transmitted by aphid, and severe yield losses may reach up to 100%

[z] Color of potato chips is an index for evaluating their quality

[aa] Many genes controlling multiple yield traits were introgressed in to *G. max* from a wild species *G. soja*

[ab] SDS, caused by *Fusarium solani*, can result in slight to 100% reduction in yield

[ac] Root and stem rot causes yield losses ~4–6% each year but may reach up to 100% under heavy rains

[ad] It is transmitted by aphid. Typical symptoms are stunting of the plants with few dwarfed and flattened pods which are without hairs and even without seeds

[ae] Phytoestrogen content is a quality determinant features which is controlled by 6–12 loci

[af] The disease is caused by *Erysiphe pisi*, and reduces yield up to 15%. Resistance to the disease is controlled by three genes

[ag] It is caused by a fungus *Ascochyta rabiei*. It spreads through wind and rain-splashes. High disease severity dries up the plant quickly

Table 2 DNA-based marker resources available for various leading crops of the world

Crop	SSRs[a]	ESTs[b]	Sequencing*	References	Databases
Maize	2807	2019971	Completed	Lawrence et al., 2007; Li et al., 2008; Liang et al., 2008	http://www.gramene.org; http://www.sdwgi.com; http://www.maizegdb.org
Rice	15687	1269116	Completed	Li et al., 2008; Liang et al., 2008	http://www.gramene.org; http://www.sdwgi.com
Wheat	1603	1121459	In progress	Li et al., 2008; Liang et al., 2008	http://www.gramene.org; http://www.sdwgi.com
Barley	226	532161	In progress	Li et al., 2008; Liang et al., 2008	http://www.gramene.org; http://www.sdwgi.com
Sorghum	260	242598	Completed	Li et al., 2008; Liang et al., 2008	http://www.gramene.org; http://www.sdwgi.com
Cotton	9358	376517	In progress	Blenda et al., 2006; Li et al., 2008	http://www.cottonmarker.org; http://www.sdwgi.com
Tomato	519	293182	In progress	Mueller et al., 2005	http://www.sgn.cornell.edu; https://www.bioinformatics.nl
Potato	1053	241130	In progress	Bae et al., 2008	https://www.bioinformatics.nl
Soybean	3395	1454433	Completed	Cregan et al., 1999; Gonzales et al., 2005; Li et al., 2008; Lightfoot, 2008	http://soybase.org; http://www.comparative-legumes.org; http://www.sdwgi.com
Common bean		107213	In progress	Gonzales et al., 2005	http://www.comparative-legumes.org
Peas		10447	In progress	Gonzales et al., 2005	http://www.comparative-legumes.org
Chickpea	698	34450	In progress	Taran et al., 2007; Anbessa et al., 2009	http://www.comparative-legumes.org; http://www.icrisat.org; http://www.icarda.org
Brassica	2482	841970	In progress	Suwabe et al., 2002	http://www.brassica.info; https://www.bioinformatics.nl
Cucumber	200	18542	In progress	Fazio et al. 2003a, b; Robbins & Staub, 2009	http://www.icugi.org; http://www.vegmarks.nivot.affrc.go.jp

*ncbi (http://www.ncbi.nlm.nih.gov)

[a] These are microsatellite markers which have been used in developing linake maps followed by identfying DNA markers

[b] These are expressed sequence tags (ESTs) representing the expressed part of the genome(s). Many of the ESTs also contain repititive elements (EST-SSRs) that reveal polymorphisms not only within the source taxa, but in the related plant taxa as well. These sequences provide a considerable scope for initating comparative mapping studies

simple (Ho et al. 2002; Morris et al. 2003) or complex traits (Bouchez et al. 2002; Willcox et al. 2002).

Predicting hybrid performance in maize without making and evaluating thousands of single-cross combinations has been a goal of many hybrid breeding programs using DNA markers and/or phenotypic data (Stuber et al. 1999). QTLs associated with seven major traits were mapped using a cross B73/Mo17. Heterozygotes containing a QTL for grain yield have shown hybrid vigor relative to the respective homozygotes with only one exception suggesting not only overdominance or pseudooverdominance but also showing a significant role of the identified QTLs in heterosis. This conclusion was reinforced by a high correlation between grain yield of genotypes and the proportion of heterozygous markers across their genomes (Stuber et al. 1992).

In maize, under drought, which causes ~15% yield losses annually, a delay in silking before or during flowering results in long anthesis-silking interval (ASI). Correlation has been found between reduced anthesis-silking interval and improved yields under drought stress. DNA markers were identified for four genomic regions in maize for the expression of both yield and anthesis-silking interval (Ribaut et al. 1997). Three of these regions contributed alleles for short anthesis-silking interval corresponding to high grain yield, while one of the genomic regions showed allelic contribution for short anthesis-silking interval with low grain yield. In another study, drought tolerance in CML247, an elite tropical inbred line, was improved through introgressing five genomic regions from a donor line Ac7643 using MAS. Some genotypes performed two to four times better than the control genotype, and were selected for developing new cultivars (Ribaut et al. 2004).

Marker-assisted backcrossing, described in tomato (Paterson et al. 1988), has been utilized in maize to monitor the transfer of favorable alleles linked with QTLs (foreground selection) and to accelerate the return to the recipient genotype of the rest of the genome (background selection) (Bouchez et al. 2002). Seedling emergence was increased in sweet corn through monitoring the transfer of a QTL with positive impact on yield (Yousef and Juvik 2002). Comparison of multiparental connected designs to biparental populations for MAS and phenotypic selection in maize was done. QTLs detected for flowering time and grain yield in maize confirmed the advantage of multiparental connected designs over biparental populations (Blanc et al. 2008).

For improving resistance to Diatraea spp, a kind of insect pest, MAS was found less efficient than conventional phenotypic selection, however, combining marker and phenotypic data increased the relative efficiency by 4% in comparison to conventional phenotypic selection. Marker assisted selection for improving host plant resistance against *Diatraea* spp. seems to be of little promise unless additional QTLs with large effects are available or the costs of marker assays are considerably reduced (Bohn et al. 2001).

Maize streak virus disease is responsible for poor maize production in tropical Africa, contributing up to 100% yield loss. QTLs conferring resistance to maize streak virus in maize populations of S4 families has been mapped using a cross MAL13 (resistant source)/MAL9 (susceptible genotype). Resistance was evaluated in replicated field trials under artificial inoculation while selecting using microsatellite markers (Lagat et al. 2008).

Categorization of genetic diversity is valuable for assisting breeders in parental line selection and breeding system design. Lu et al. (2009) identified high-quality markers by screening maize inbred lines with single nucleotide polymorphism (SNP) markers while germplasm-specific biasing effects were not detected. Pairwise comparisons across three distinct sets of germplasm, CIMMYT (394), China (282), and Brazil (94), suggested that utilization of genetic diversity existing in the center of origin was limited in the development of elite lines from these diverse breeding pools. Long-term selection for hybrid performance has contributed to significant allele differentiation between heterotic groups at 20% of the single nucleotide polymorphism loci. There were considerable levels of genetic variation between different breeding pools which was reflected by missing and unique alleles. There were two SNPs which were developed from the same candidate gene associated with the divergence between two respective Chinese heterotic groups. A linkage disequilibrium block of 142 kb was indicated by associated allele frequency change at two SNPs and their allele missing in Brazilian germplasm. SNP markers have been proven to be powerful for diversity analysis and also a practicable approach to unique allele discovery and use in maize breeding programs (Lu et al. 2009).

4.1.2 Rice

Bacterial blight is one of the most destructive diseases of rice, causing up to 50% losses in yield. Sequence tagged site markers associated with three bacterial blight resistant genes, *xa*5, *xa13* and *Xa21* (Chunwongse et al. 1993; Huang et al. 1997) were pyramided through marker-assisted backcrossing in a high yielding susceptible rice cv. PR106 (Singh et al. 2001). In another investigation, two genes *Xa7* and *Xa21* were pyramided for the improvement of resistance to bacterial blight in hybrid rice using MAS (Zhang et al. 2006).

Basmati rice is highly susceptible to bacterial blight, and transfer of resistant genes from non-Basmati sources through cross-hybridization requires strict monitoring for recovery of the essential Basmati quality traits. Background analysis using mapped SSRs was integrated with foreground selection to identify superior lines combining the distinctive quality features of Basmati with useful resistant genes (*xa13* and *Xa21*) derived from a non-Basmati resistant donor line IRBB55. One of the lines (Improved Pusa Basmati 1) has been commercialized in India, developed through MAS (Gopalakrishnan et al. 2008). Similarly, microsatellite markers associated with three major resistance genes (*Xa21*, *xa13* and *xa5*) were introgressed into an elite indica rice variety (Samba Mahsuri) through marker-assisted backcrossing (Sundaram et al. 2008).

Blast, caused by a fungus *Magnaporthae grisea,* is one of the most detrimental diseases of rice. Three major genes (*Pi*1, *Piz*-5 and *Pi*ta) conferring resistance to the disease were fine-mapped on chromosomes 11, 6 and 12, respectively, pyramided through MAS using tightly linked RFLP markers (Hittalmani et al. 2000). Enhanced expression of resistance was observed in genotypes containing at least two or three genes together.

A total of 76 QTLs associated with morphological traits and yield components were identified using a population developed from a cross between *Oryza rufipogon* var IRGC 105491 and *O. sativa* ssp. japonica cv. Jefferson (Thomson et al. 2003). Novel alleles derived from *O. rufipogon* have stable effects in multiple genetic backgrounds and environments. In another study, 42 QTLs were identified for 12 agronomic traits in rice, among which 14 QTL alleles derived from *O. rufipogon* had beneficial impacts on yield components in *O. sativa* background (Septiningsih et al. 2003). Some QTLs reported in rice together with QTLs identified in maize (Thomson et al. 2003) appeared well conserved across the grass families (Septiningsih et al. 2003) and may be useful in initiating MAS in other members of the grass family.

Root traits exhibit positive associations with yield and its components under drought conditions. Through MAS four QTLs linked with deeper root systems were introgressed from Azucena (*japonica* variety) into IR64, which increased root length by 12–27% (Shen et al. 2001). A QTL for osmotic adjustment mapped on chr-8 in rice under drought (Robin et al. 2003), showed correspondence with a region containing QTLs for relative water content under water stress condition on chr-7 (Morgan and Tan 1996) and chr-1 (Teulat et al. 2003) of wheat and barley, respectively. Similarly, a QTL for osmotic adjustment in rice was found on chr-3 which is syntenic to maize chr-1. This maize region was associated with various physiological and agronomic traits influencing drought tolerance (Zhang et al. 2001). These investigations indicate the conservativeness of these regions associated with better performance under drought in wheat, rice, barley and maize. Here, DNA markers can be used for diagnosing plants containing QTLs for favorable allele (Nguyen et al. 2004).

Spikelet sterility is often caused by the lack of viable pollen at low temperature. A tight association was found between a single nucleotide polymorphism (alternative oxidase gene, *OsAOX1a*) with two closely linked QTLs (Ctb_1 and Ctb_2) conferring tolerance to low temperature in anthers (Abe et al. 2002). One of the QTLs (Ctb_1) has been physically mapped and seven candidate genes were recognized for this QTL. The identified single nucleotide polymorphism can be useful in MAS for diagnosing plants containing QTL for cold tolerance (Saito et al. 2004).

Two QTLs with major effects, one (qSNC-7) on chr-7 for shoot Na^+ reduction and second (*qSKC-1*) on chr-1 for shoot K^+ accumulation were pyramided in three F_3 lines derived from a cross IR64 (moderate tolerant)/Azucena using MAS (Lin et al. 2004). In another study, a QTL explaining 19.6% of the variation for K^+ uptake was identified on chr-9 (Koyama et al. 2001). A major QTL designated Saltol on chr-1 (explaining 43% of the variation for seedling shoot Na^+/K^+ ratio) was identified (Bonilla et al. 2002). Seven QTLs associated with salt stress explaining less than 20% of the variation for seedling traits were mapped (Prasad et al. 2000). Several QTLs for shoot length and number of tillers per plants under saline conditions were reported (Takehisa et al. 2004). All these QTLs were assembled in one genotype through marker-assisted backcrossing scheme.

Marker-assisted selection has successfully been employed for improving the quality of rice grain by introgressing a Waxy gene allele derived from Minghui-63 into Zhenshan-97A using tightly linked microsatellite and RFLP markers. A total of 118 AFLPs were used in background selection to recover the genetic background of Zhenshan at unlinked loci (Zhou et al. 2003a). Introgression of one QTL for grain number, and one QTL for plant height were pyramided into the same genetic background, which resulted in higher yield of the newly bred rice strain (Ashikari et al. 2005).

Blast disease is a destructive fungal disease of rice. Race-specific resistance to blast disease has not proven to be an effective technology. Cloning of a previously unknown type of gene that confers non–race-specific resistance has been reported and further it has been successfully used in breeding. A proline-rich protein that includes a putative heavy metal–binding domain and putative protein-protein interaction motifs is encoded by *Pi21*. Wild-type *Pi21* causes slowing down of the plant's defense responses, which can support optimization of defense mechanisms. This slowing down process is inhibited by deletions in its proline-rich motif. *Pi21* is separable from a closely linked gene conferring poor flavor. The resistant *pi21* allele, which is found in some strains of *japonica* rice, was able to improve blast resistance of rice (Fukuoka et al. 2009).

The stub-spreading trait, which is also designated as 'tiller angle', is one of the determinants of plant type. This trait is quite important in rice due to its contribution to yield performance. The *Spk*(t) gene is a major contributor of the trait in the cross of 'Kasalath' (*indica*) and 'Nipponbare' (*japonica*). The *Spk*(t) gene was isolated by a map-based cloning strategy by Komori et al. 2009. *Spk*(t) and *spk*(t) transcripts were shown to encode identical 259-aa proteins of unknown function after sequence analysis of cDNA clones from the locus; however, the structure of the 3′-untranslated region of each allele is quite different. Further transgenic experiments in rice verified that the difference is caused by a single-nucleotide polymorphism at the 3′-splicing site specific to the *Spk*(t) allele which perform a crucial role in phenotypic expression. This information will be useful for rice breeding, in addition to revealing the molecular mechanism underlying allele differentiation at the *Spk*(t) locus.

4.1.3 Wheat

Leaf rust, caused by a fungus *Puccinia recondita*, is one of the major causes of yield losses in wheat (*Triticum aestivum* L.). Two slow rusting genes *Lr34* and *Lr46* were found effective against different pathotypes of the fungus (Singh et al. 1998). Hypersensitive resistance responses have been derived by combining *Lr34* with any of the other *Lr* genes (Kolmer 1996; Kloppers and Pretorius 1997). Molecular markers have been identified for *Lr34* (Suenaga et al. 2003) and other leaf rust genes (Huang and Gill 2001), which can be utilized in breeding for enhanced resistance against the rust. The first wheat variety containing stripe rust resistance gene *Yr17* and leaf rust resistance gene *Lr37* developed through marker assisted selection, is 'Patwin' which has been commercialized by the University of California at Davis (http://www.plantsciences.ucdavis.edu; Helguera et al. 2003). In another study, two cereal cyst nematode resistance genes from *Aegilops variabilis* in wheat (Barloy et al. 2007) and introgression of leaf rust resistance genes *Lr1*, *Lr9*, *Lr24*, *Lr47* into bread wheat cultivars through MAS (Nocente et al. 2007) have been reported. Yellow or stripe rust caused by *Puccinia striiformis* f. sp. *tritici* (Pst), is one of the most devastating wheat diseases. *Triticum aestivum* × *Haynaldia villosa* 6VS/6AL translocation lines carrying the *Yr26* gene on chromosome 1B are resistant to most races of Pst. Microsatellite and sequence tagged site based marker loci (*Xwe173* and *Xbarc181*) were used in MAS for incorporating *Yr26* into wheat cultivars (Wang et al. 2008). Recently, two genes *Yr5* and *Yr15* imparting resistance against stripe rust at all stages of wheat plant. Previously reported markers for these genes were not effective in diagnosing resistant plants. Newly identified sequence tagged site marker STS7/8 and *Xbarc349* and *Xbarc167* flanking the *Yr5* gene were not equally effective in all genetic backgrounds. However, microsatellite markers *Xbarc8* and *Xgwm413* flanking the *Yr15* appeared to be diagnostic in all genetic backgrounds with one exception (Murphy et al. 2009).

Resistance to a newly emerged strain of stem rust (Ug99), another devastating disease of wheat (*Triticum aestivum* L.) worldwide, has been deployed through transferring *Sr40* gene from *T. timopheevii* ssp. *armeniacum* to wheat. A marker locus *Xwmc344* closely linked to *Sr40* (0.7 cM) was identified followed by the identification of two markers *Xwmc474* (~2.5 cM) and *Xgwm374* in the flanking region of the gene, which could be useful in marker-assisted integration and pyramiding of *Sr40* into elite wheat breeding lines (Wu et al. 2009).

The stem rust resistance gene *Sr39* is known to provide resistance to all presently known pathotypes of *Puccinia graminis* f. sp. *tritici* (Pgt) including Ug99 (TTKSK) and was introgressed together with leaf rust resistance gene *Lr35* accounting for adult plant resistance to *P. triticina* (Pt), into wheat from *Aegilops speltoides*. Due to the anticipated but not documented negative agronomic effects associated with *Ae. speltoides* chromatin it has not been used extensively in wheat breeding. Mago et al. (2009) reported the production of a set of recombinants with shortened *Ae. speltoides* segments through induction of homoeologous recombination between the wheat and the *Ae. speltoides* chromosome. Simple PCR-based DNA markers have been developed for resistant and susceptible genotypes (Sr39#22r and Sr39#50s). These markers can facilitate the pyramiding of ameliorated sources of *Sr39* with other stem rust resistance genes that are effective against the Pgt pathotype TTKSK and its variants in further breeding programmes.

A new race of the pathogen named TTKSK (syn. Ug99) and its derivatives detected in East Africa are for a threat to many characterized and uncharacterized stem rust resistance genes. Global wheat production is threatened by the emergence and spread of those races. Genes *Sr25* and *Sr26* transferred into wheat from *Thinopyrum ponticum* were found effective against these new races. The co-dominant markers for *Sr25* and *Sr26* have been authenticated with 37 lines with known stem rust resistance genes. This information can be further utilized in breeding programmes (Liu et al. 2010).

Three QTLs associated with resistance to powdery mildew were mapped (Liu et al. 2001), and microsatellite markers associated with *Pm4a* and *Pm5e* (Huang et al. 2003; Ma et al. 2004) and STS_241, Me8/Em7_220 and *Xgwm382* associated with another resistance gene *Pm4b* were identified which could be used for MAS in wheat breeding programmes (Yi et al. 2008). A major QTL conferring resistance to scab disease was validated with microsatellite markers which were used for initiating MAS in wheat breeding program (Zhou et al. 2003b).

A gene for Al tolerance, Alt_{BH} was identified on the long arm of chr-4D in bread wheat (Riede and Anderson 1996) and one of the microsatellite markers (*Bmag353*) linked to this locus (Raman et al. 2003) was used to probe Al tolerant F_3 plants with more than 95% accuracy. Miftahudin et al. (2002) discovered that there are conserved genomic region on the long arm of homoeologous chr-4 for Al tolerance among wheat (Alt_{BH}), rye (*Alt3*) and barley (*Alp*), showing a high level of synteny among chromosomes 4DL, 4RL and 4HL, which will be useful source in MAS in many cereals (Nguyen et al. 2003).

Polymorphisms in sequences of coding and promoter regions of a locus *Glu-1*, involved in conferring bread making quality in wheat, were identified (Ma et al. 2003; Radovanovic and Cloutier 2003). Multiplexed PCR was established for discrimination of major HMW glutenins in single assay. Two specific PCR based markers were also validated and used to distinguish alleles at *Glu-B1x* locus for improving the bread making quality through MAS (Xu et al. 2008a).

Durum wheat (*Triticum turgidum* L. subsp. *durum*, 2n=*4x*=28, AABB), known for making pasta products, has received less attention than bread wheat in genetic and genomic studies. A tetraploid wheat doubled haploid population consisting of 146 lines was derived from a cross *T. tugidum* var Lebsock/*T. turgidum* subsp. *carthlicum* accession PI 94749 (Chu et al. 2010). This population was further used to construct linkage maps of all 14 chromosomes comprising of 280 microsatellite markers, and also for identification of QTLs associated with tan spot resistance. Results of this study together with those of other similar studies have shown that the wheat–*P. tritici-repentis* pathosystem involves more factors than presently published host-toxin interactions. The doubled haploid population and genetic maps would set a stage for genetic analysis of important agronomic traits (Chu et al. 2010).

4.1.4 Barley

Two major QTLs (QTL1 and QTL2) associated with malt extract percentage, alpha-amylase activity, diastatic power, and malt beta-glucan content identified on chr-1 and chr-4 of barley (*Hordeum vulgare*), showed stable expression across different ecological zones. Survey of RFLPs *Brz* and *Amy2* associated with QTL1 found effective in selection of desirable barley plants (Han et al. 1997). In another investigation, QTLs identified for grain and malt quality traits were located on chr-3, chr-6 and chr-7, with QTLs discovered on chr-7 most useful in selecting superior genotypes (Igartua et al. 2000). High yielding near isogenic lines containing conventional malting quality were developed using restriction fragment length polymorphism-based marker-assisted backcrossing by transferring QTL associated with yield. In multilocation tests, one line coupling high yielding potential of one parent (Baronesse) with malting quality of the other parent (Harrington) was selected (Schmierer et al. 2005).

Two tightly linked QTLs for tolerance to low temperature found on chr-5 of barley (Francia et al. 2004) co-occurred with QTLs regulating levels of mRNA (Vagujfalvi et al. 2003) and protein accumulation encoded by cold-regulated (COR) genes. Two tightly linked RAPD, and sequence tagged site markers derived from the sequence of wheat RFLPs, were surveyed in two sets of winter and spring barley genotypes and in doubled haploid lines for the assessment of frost tolerance level (Toth et al. 2004). Both type of DNA markers effectively distinguished the frost tolerant and susceptible genotypes in MAS.

Three DNA markers (RAPD, SCAR and STS) tightly linked to a gene (*Ruhq*) conferring resistance to covered smut disease in hulled barley were used for introgressing the gene into hulless barley (Grewal et al. 2008) through doubled haploidy and marker-assisted backcrossing procedures. Similarly, a gene (*Run8*) imparting resistance to loose smut disease was also introgressed into a hulless barley cultivar through double haploidy and marker-assisted backcrossing methods. One line (HB390) developed through MAS was evaluated in the Western Canadian Hulless Barley Co-operative yield trials before commercial release in Canada. In another study, Schmalenbach et al. (2008) generated a set of introgression lines in spring barley by three rounds of backcrossing, two to four subsequent selfings, and, in parallel, MAS. The effectiveness of these introgression lines set was demonstrated by verification of QTLs controlling resistance to powdery mildew (*Blumeria graminis* f. sp. *hordei* L.) and leaf rust (*Puccinia hordei* L.).

Development of robust, allele-specific PCR markers for codominant SNP genotyping on agarose gels by temperature-switch PCR has been demonstrated by Hayden et al. (2009). A total of 87 TSP markers were developed in barley for assessing gene diversity and were evaluated regarding efficacy for marker development, assay reliability and genotyping accuracy. The temperature-switch PCR markers provided good coverage of the genome, usability and ease in scoring and interpreting and assay automation. temperature-switch PCR markers are expected to provide similar advantages in breeding for any animal or plant species (Hayden et al. 2009).

4.1.5 Sorghum

Sorghum is a C4 grass, and is a source of food, feed, fiber and biofuel, especially in the semi-arid tropics. Its genome (~730 Mbp) has been sequenced, and the information can be transferred to its closet relatives (maize, wheat etc.) for developing fine genetic linkage map which will pave the way for initiating MAS in the grass family (Paterson et al. 2009).

Stay-green in sorghum is one of the most important mechanisms conferring drought resistance, for which several QTLs (*Stg1*, *Stg2*, *Stg3* and *Stg4*) were identified using various populations (Haussmann et al. 2002; Sanchez et al. 2002; Harris et al. 2007). Out of these, *Stg2* was used to develop sorghum NILs through marker-assisted backcrossing (Sanchez et al. 2002). Later, 18 different near isogenic lines were developed through MAS that contained introgressed regions of the four major stay-green loci, *Stg1–Stg4*.

Tolerance to early season cold is a quantitative trait, and several QTLs linked with microsatellite markers were identified. These microsatellite markers were validated for initiating MAS for tolerance to early-season cold in various genetic backgrounds and environments (Knoll and Ejeta 2008).

A RAPD marker $OPJ01_{1437}$ associated with resistance to Anthracnose disease was mapped and converted into serquence characterized amplified region (SCJ01) which showed correspondence to contig-3966 located on chr-8 of sorghum genome which could be used in diagnosing resistant plants (Singh et al. 2006).

One of the most damaging insect pests of sorghum at the seedling stage is the shoot fly. A microsatellite marker-based linkage map was constructed using recombinant inbred lines of the cross 296B (susceptible) × IS18551 (resistant) by Satish et al. (2009). A total of 29 QTLs were detected by multiple QTL mapping viz., four each for leaf glossiness and seedling vigor, seven for oviposition, six for deadhearts, two for adaxial trichome density and six for abaxial trichome density. For most of the QTLs, resistance alleles were contributed by IS18551; however, at six QTLs, alleles from 296B also contributed to resistance. Some QTLs identified in this study corresponded to QTLs/genes for insect resistance at the syntenic maize genomic regions, which implies conservation of insect resistance loci between these crops. The QTLs identified in the study will offer a foundation for MAS programs for improving shoot fly resistance in sorghum.

4.2 Family: Malvaceae

4.2.1 Cotton (*Gossypium sp.*)

Cotton is the world's most important natural textile fiber (Rahman et al. 2008a). Sustainability in lint production and its quality can be obtained by employing modern genomic tools to discover DNA polymorphisms and their utility in MAS (Rahman et al. 2009). Community resources like an integrated web database (Gingle et al. 2006), cotton microsatellite database (Blenda et al. 2006), and comparative QTL resource (Rong et al. 2007) along with sequencing data for *Gossypium* can accelerate the progress towards initiating marker assisted selection in cotton improvement programs (Chen et al. 2007).

Two QTLs (t_1 and t_2) were found on chr-6 and chr-25, respectively, for dense leaf pubescence in cotton. Other QTLs with significant phenotypic variation in leaf pubescence were designated as t_3, t_4, t_5 (Wright et al. 1999). In another study

RAPDs and microsatellite markers linked to hairiness, nectariless and red leaf color traits were identified (Rahman et al. 2002a; Rahman et al. 2003; Ali et al. 2009). Water stress is one of the major factors for reduction in cotton production. Different QTLs have been found that can be potentially be utilized for MAS in cotton under water stress conditions (Saranga et al. 2001; Paterson et al. 2003; Ullah 2009).

One RAPD marker linked with gene which restore male-fertility was discovered in upland cotton. This marker was sub-cloned, sequenced, and mapped to a cotton high density RFLP map (Lan et al. 1999). Furthermore, RAPD markers associated with two dominant restorer genes (Rf_1 and Rf_2) were identified in two cotton lines of D_2 genome which are useful in MAS for developing restorer parental lines (Zhang and Stewart 2004; Feng et al. 2005).

Four RAPDs and two microsatellite markers associated with resistance to cotton leaf curl disease (CLCuD) were identified (Rahman 2002; Rahman et al. 2006). These markers were utilized in monitoring the transfer of resistance in succeeding generations which resulted in the development of two resistant cotton lines NIBGE-2 (Rahman and Zafar 2007b) and NIBGE-115 (Rahman and Zafar 2007a). In another study, three RFLP markers associated with resistance to the virus disease were identified using an interspecific $F_{2:3}$ population [*G. barbadense* (highly suspectible genotype)*/G. hirsutum* (resistant genotype)] (Aslam et al. 1999).

Fusarium wilt causes yellowing, wilting, defoliation, vascular tissue damage and ultimately death in cotton. An intraspecific (*G. hirsutum*) F_2 population was developed by crossing a highly resistant cultivar ZMS35 with a susceptible cultivar Junmian-1 to find linked markers associated with fusarium wilt resistance. Molecular mapping identified a fusarium wilt resistance gene closely linked with an microsatellite marker JESPR304_{-280} on chromosome D3 (c17). With composite interval mapping, four QTLs were detected. Among them, one major QTL (LOD > 20) was tagged near marker JESPR304 within an interval of 0.06–0.2 cM, and explained over 52.5–60.9% phenotypic variance. It provides an opportunity to conduct MAS to develop fusarium wilt resistant cultivars (Wang et al. 2009).

DNA markers linked to fiber quality traits can be utilized for MAS in cotton (Zhang et al. 2003; Asif 2009). QTLs for fiber strength were identified using a population from a cross between *Gossypium hirsutum* (TM-1) and a *G. anomalum* introgression line 7,235 (Zhang et al. 2003). Nine DNA markers (three microsatellite markers and six RAPD markers) were linked to two QTLs for fiber strength mapped into one linkage group. One major 'QTLFS1' explaining 30% of phenotypic variation was transfered in four different genetic backgrounds using the linked RAPD and microsatellite markers. Later on, one of the random amplified polymorphic DNA markers converted into reliable SCAR (SCAR431_{1920}) was successfully applied to large scale screening for the presence or absence of the major QTL linked with fiber strength in cotton molecular breeding program (Guo et al. 2003). Recently, Chen et al. (2009) fine mapped this major fiber strength QTL on Chr-24 (D8).

Restriction fragment length polymorphism markers in an interspecific (*G. hirsutum* x *G. barbadense*) population associated with some important fiber quality related

QTLs were identified (Chee et al. 2005a, b; Draye et al. 2005). Markers associated with the QTLs coming from *G. barbadense* may help in MAS breeding for high quality lint production in cotton (Chee et al. 2005b). Also, microsatellite markers were successfully used to monitor the introgression of genomic regions derived from *G. barbadense* into *G. hirsutum* which escalated 12–20% increase in fiber length (Mumtaz 2007). Amplified fragment length polymorphisms associated with fiber and agronomic traits were identified in cotton recombinant inbred lines which could also be used in MAS (Jixiang et al. 2007).

Wu et al. (2009) evaluated recombinant inbred lines developed from F_2-derived families and their two parental lines, 'HS 46' and 'MARCABUCAG8US-1-88', for two years. Microsatellite markers were used to construct 26 linkage groups, spanning 965 cM, out of these 24 linkage groups were assigned to chromosomes. Fifty-six QTLs (LOD > 3.0) associated with 14 agronomic and fiber traits were located on 17 chromosomes. One QTL associated with fiber elongation was located on linkage group LGU01. Nine chromosomes in the A subgenome harbored 27 QTLs with 10 associated with agronomic traits and 17 with fiber traits. Eight chromosomes in the D sub-genome contained 29 QTLs with 13 associated with agronomic traits and 16 with fiber traits. Chromosomes number 3, 5, 12, 13, 14, 16, 20, and 26 of which contain important QTLs for both yield and fiber quality compared to other chromosomes. These QTLs were detected in intraspecific regions thus may have utility in MAS (Wu et al. 2009).

4.3 Family: Solanaceae

4.3.1 Tomato

In pioneering experiments elucidating the possibilities of using DNA markers in crop improvement programs, four markers representing three chromosomal regions, controlling the soluble solids and pH, were introgressed from wild tomato (*L. chmielewskii*) in cultivated tomato species (*L. esculentum*, Tanksley and Hewitt 1988). In another study, six QTLs controlling fruit mass, four QTLs for the concentration of soluble solids and five QTLs for fruit pH were mapped using a population derived from intraspecific backcross (Paterson et al. 1988).

A QTL for increased soluble solid contents was introgressed into cultivated tomato from *L. chmielewskii* chr-1, and near isogenic lines were developed through marker-assisted introgression (Frary et al. 2003). Similarly, marker-assisted backcrossing method was used for recovering five QTLs linked with fruit quality traits into three different genetic backgrounds of cultivated tomato. It was demonstrated that three backcrosses were enough to recover much of the recipient genome (Lecomte et al. 2004).

Molecular markers are valuable diagnostic tools for tracing the recessive or incompletely dominant resistant genes. Identification of five RAPD markers, converted into SCARs (Paran and Michelmore 1993), and two RFLP markers

(Huang et al. 2000) around a gene *Ol-1* conferring incomplete dominance resistance to tomato powdery mildew (*Oidium lycopersicum*) disease set the stage for map-based cloning and MAS (Huang et al. 2000). Resistance to Blackmold, caused by the fungus *Alternaria alternata*, has been found in a wild tomato (*L. cheesmanii*), and was recovered in cultivated tomato species using RFLP and PCR-based markers (Robert et al. 2001).

Tomato cultivars are sensitive to drought especially at seed germination and early seedling growth stages. Four QTLs impacting germination rate under drought were identified using a population derived from a cross between a commercial line of *L. esculentum* and *L. pimpinellifolium* (Foolad et al. 2002). These QTLs could potentially be used to increase the germination rate in tomato through marker assisted breeding.

Molecular markers linked to phenotypically important traits which are difficult and/or costly to measure are very useful. Biological assays for evaluation of disease traits are often influenced by environmental factors, and scoring is difficult. The development and/or evaluation of molecular marker assays for the Verticillium genes *Ve1* and *Ve2*, the *tomato mosaic virus Tm1* (linked marker), the tomato mosaic virus *Tm2* and *Tm2* ^{2} genes, the *Meloidogyne incognita Mi1-2* gene, the Fusarium *I* (linked marker) and *I2* loci was described by Arens et al. (2010). Marker assays showed an advantage over biological tests in that the results were clearer.

In tomatoes the *Sw-5* locus is reported to be responsible for the best levels of broad-spectrum *Tospovirus* resistance. *Sw-5b* represents the actual resistance gene out of the five paralogues of this locus (denoted *Sw-5a* through *Sw-5e*). A panel of seven PCR primer pairs matching different sequences within a genomic region spanning the *Sw-5a* and *Sw-5b* genes cluster was evaluated. Primers efficiency was evaluated by employing tomato isolines with and without the *Sw-5* locus. A single and co-dominant polymorphism between susceptible and resistant isolines was produced by one primer pair. After sequence analysis of these amplicons it was found that they were specific for the *Sw-5* locus and their differences were due to insertions/deletions. A conserved sequence of the promoter region of the functional *Sw-5b* gene, being located in position −31 from its open reading frame was encompassed by the polymorphic SCAR amplification. An almost complete correlation was found between resistance under greenhouse/field conditions and the presence of the marker after evaluation in field assays and with a collection of accessions known to be either susceptible or resistant to tospoviruses. This primer pair was found to be a useful tool in MAS (Dianese et al. 2010).

4.3.2 Potato (*Solanum sp.*)

Chip color in potato is influenced by the sucrose synthase gene. A polymorphic allele associated with chip color has been identified and used in marker assited selection for developing potato cultivars (Kawchuk et al. 2008). For better water-use efficiency, a QTL representing introgressed fragment from *S. pennellii* was used for diagnosing F_2 plants with introgressed fragment in marker assisted breeding (Xu et al. 2008b).

Genes conferring resistance to viruses, bacteria, nematodes, and fungi have been positioned on the molecular map of potato using DNA markers, and the QTLs associated with resistance genes were identified to launch marker-assisted breeding (Naess et al. 2000; Gebhardt and Valkonen 2001). Some of the QTLs for resistance to different pathogens were linked to each other and/or to resistance hotspots. Mapping potato genes with sequence similarity to cloned R genes from other plants and other defense-related genes has revealed linkages between candidate genes, R genes, and QTLs associated with resistance, suggesting that the "candidate gene approach" is useful for detecting important DNA markers in potato.

A wild potato (*S. stoloniferum*) carries the Ry_{sto} gene that confers extreme resistance to Potato virus Y. This gene was introgressed into cultivated potato using RFLP based cleaved amplified polymorphic sequence and microsatellite markers (Song et al. 2005; Valkonen et al. 2008). Tomato *Ve1* and *Ve2* gene sequence information (conferring resistance to verticillium wilt) was used to amplify candidate *Ve* gene orthologs from both verticillium wilt resistant and susceptible diploid potato hybrids. On the basis of this information a cleaved amplified polymorphic sequence marker associated with verticillium wilt resistance was developed and effectively used to select verticillium wilt resistant plants in diploid potato populations (Bae et al. 2008).

Solanum tuberosum ssp. *andigena* gene Ry_{adg} provides extreme resistance to Potato virus Y. This gene was genetically mapped to chromosome XI and PCR-based DNA markers linked with this gene were also identified. Advanced tetraploid russeted potato clones developed by the U.S. Pacific Northwest Potato Breeding ('Tri-State') Program with Ry_{adg} Potato virus Y resistance were used to assess the usefulness of molecular markers linked to Ry_{adg}. These markers can further be used as a tool for selecting Potato virus Y resistance in a tetraploid potato breeding program which are a better alternative to artificial inoculation followed by ELISA. Marker assisted selection can simplify generating Potato virus Y resistant potato varieties (Ryon et al. 2009).

4.4 Family: Fabaceae

4.4.1 Soybean

An important yield QTL was identified in an accession of *Glycine soja* (PI 407305) by evaluating a BC_2 population (HS-1 and PI 407305), which was introgressed into six genetic backgrounds through marker assisted backcrossing. This QTL contributed 9.4% yield advantage to two of the six genetic backgrounds (Concibido et al. 2003).

To widen the narrow genetic base of elite soybean germplasm (*G. max*), five backcross populations (BC_2F_4, 468 lines) derived from a cross of *G. max* cv. A2008/*G. soja* acc. 468916, tested for 2 years at two different locations. Four yield QTLs, one lodging QTL, four QTLs for maturity, and five QTLs for plant height were identified. Most QTLs mapped to regions where QTLs with similar effects were previously mapped. Alleles derived from *G. max* cultivar conferred higher yield than alleles from *G. soja* (Wang et al. 2004). Also, microsatellite marker Sat_107 closely associated with the four-seeded pod (4SP) locus was effective in selecting plants for this trait (Zhu and Sun 2006). Understanding the mechanism of canopy wilting in soybean may lead to yield improvement during drought. Charlson et al. (2009) used recombinant inbred lines population to identify QTLs for canopy wilting under three environments. Four QTLs on molecular linkage groups (MLGs) A2, B2, D2, and F were detected, which collectively accounted for 47% of phenotypic variation.

Seed yield mega-environment-universal and specific QTL ($\mathrm{QTL}_{\mathrm{U}}$ and $\mathrm{QTL}_{\mathrm{SP}}$, respectively) were identified in a RIL population derived from a cross between a Chinese and a Canadian soybean. Seven seed yield QTL were identified of which five were mega-environment universal QTL and two were mega-environment-specific QTL. Four yield $\mathrm{QTL}_{\mathrm{U}}$, tagged by microsatellite markers (Satt100, Satt277, Satt162 and Sat_126), were co-localized with a QTL associated with an agronomic trait. It was suggested that successful introgression of productivity alleles from plant introductions into adapted germplasm could be facilitated by use of both $\mathrm{QTL}_{\mathrm{U}}$ and $\mathrm{QTL}_{\mathrm{SP}}$ (Palomeque et al. 2009a, b)

Resistance to sudden-death syndrome (caused by *Fusarium solani*) is controlled by multiple QTLs. A total of six loci involved in resistance to sudden-death syndrome showed additive gene action, elucidating that cultivars with durable resistance can be developed via gene pyramiding through MAS (Iqbal et al. 2001).

A series of resistance genes (*Rps*) have been identified against root and stem rot (caused by *Phytophthora sojae*), however, only *Rps8* has been mapped. Tightly linked microsatellite markers were identified in the *Rps8* region. Later it has been shown that the *Rps8* gene is located closely to the disease resistance gene-rich *Rps3* region (Sandhu et al. 2005), which can potentially be used for MAS in soybean.

A comparative genomic approach was used to fine map *Rsv*4 gene, conferring resistance to soybean mosaic virus, indicating the use of comparative mapping in MAS (Hwang et al. 2006).

A total of six single nucleotide polymorphisms tightly linked to QTLs for resistance to southern root-knot nematode (*Meloidogyne incognita*) were identified. Among these, SNP358 and SNP199 markers could be used effectively in MAS for developing resistance agains the disease. Application of single nucleotide polymorphisms also enhanced the efficiency and cost-effectiveness of MAS in soybean.

Resistance to soybean aphid is controlled by a single dominant gene '*Rag1*' that was mapped to soybean linkage group M between the microsatellite markers Satt435 and Satt463. These markers were exploited in MAS for breeding resistance against aphid (Li et al. 2007).

Phytoestrogen content and profile in soybean fluctuate in different environments and genotypes. However, the final seed content is largely controlled by the genotype (40–60% of the variation), mainly by a set of about 6–12 loci (Kassem et al. 2006). Heritability of phytoestrogen content is moderate, thus, direct selection (without DNA markers) has not been very effective. Through MAS phytoestrogen amounts increased well above the level found in elite cultivars, exemplifying the role of MAS toward the improvement of phytoestrogen content (Lightfoot 2008).

4.4.2 Common Beans

Common bacterial blight caused by *Xanthomonas campestris* pv. *Phaseoli* is responsible for signifcant reduction in yield of common bean (*Phaseoius vulgaris*) worldwide. A SCAR marker BC420 linked to a QTL conferring resistance to common bacterial blight, found reliable for MAS across different genetic backgrounds (Yu et al. 2000; Park and Yu 2004; Liu et al. 2005), and this marker was used to transfer the QTL in advanced bean lines, exhibiting improved resistance to common bacterial blight (Mutlu et al. 2005). This marker has been extensively used in MAS breeding programmes in different countries (Fourie and Herselman 2002; Mutlu et al. 2005; Liu et al. 2008). Effectiveness of MAS was tested for resistance to white mold (*Sclerotinia sclerotiorum*) using two recombinant inbred lines (Ender et al. 2008). Random amplified polymorphic DNA and AFLP markers were surveyed for selection of a major QTL associated with resistance and plant architectural avoidance traits. Based on two years of field evaluation under white mold pressure, ten recombinant inbred lines generated through MAS, revealed significantly less disease than the control. This study supported the usefulness of MAS to enhance selection for a complex trait in common bean.

4.4.3 Peas

Powdery mildew, caused by *Erysiphe pisi,* is a major limitation factor for yield losses (up to 15%) in peas (*Pisum sativum*), a widely grown grain legume. Three genes, *er1*, *er2* (later mapped on linkage group III, Katoch et al. 2009) and *Er3*, conferring resistance to powdery mildew were identified (Fondevilla et al. 2007). DNA markers linked to resistance genes provide an alternative to disease screening for pyramiding of powdery mildew resistance genes in pea. Random amplified polymorphic DNA, SCAR, AFLP and microsatellite markers tightly linked to these resistance genes have been identified and mapped for MAS (Tiwari et al. 1998, 1999; Janila and Sharma 2004; Ek et al. 2005; Fondevilla et al. 2007; Katoch et al. 2009). Two SCAR makers linked to *Er3* gene were successfully used to distinguish homozygous resistant F_2 plants (Fondevilla et al. 2008).

The number of offspring to be propagated, selected and tested can be reduced by merging MAS with breeding strategies. Potato breeding includes the testing of resistance to viral pathogens such as pea seed-borne mosaic virus. Resistance to the common strains of pea seed-borne mosaic virus is conferred by a single recessive gene (*eIF4E*), localized on LG VI (*sbm-1* locus). Smykal et al. (2010) have analyzed donors of resistant varieties and breeding lines for variation in the *eIF4E* genomic sequences. After complete investigation of the *eIF4E* gene structure and mutations responsible for pea seed-borne mosaic virus resistance PCR-based and gene-specific single nucleotide polymorphism and co-dominant amplicon length polymorphism markers were developed. Sequence data and/or allele specific DNA markers were tested on potato accessions. Allele specific markers which were developed were successfully surveyed on a wide range of pea varieties and breeding lines. Due to the better authenticity of these markers in comparison with the symptomology and ELISA, testing these molecular markers will considerably speed-up pea seed-borne mosaic virus diagnosis and resistance breeding processes in pea (Smykal et al. 2010).

4.4.4 Chickpea

Ascochyta blight caused by *Ascochyta rabiei* is a fungal disease in chickpea (*Cicer arietinum*). Over the last decade, attempts have been made to tag ascochyta blight resistance genes with DNA markers (Santra et al. 2000; Tekeoglu et al. 2002; Taran et al. 2007; Anbessa et al. 2009). Despite many reports of QTLs for resistance to ascochyta blight (Cho et al. 2004; Cobos et al. 2006; Iruela et al. 2007; Taran et al. 2007), applications of MAS for improving resistance against the disease are not common (Anbessa et al. 2009) due to moderate sources of resistance conferred by different genes originating from various cultivated species. Four divergent moderately resistant cultivars and one highly susceptible genotype were used followed by surveying with microsatellite markers, and five QTLs explaining 14–56% each of the phenotypic variation, were identified. These QTLs could be pyramided in one genotype for enhancing resistance against the disease (Anbessa et al. 2009). In another study, three QTLs were identified that contributed to resistance to an Indian isolate of ascochyta blight. QTL1 was mapped to LG3 linked to marker TR58. QTL2 and QTL3 were both mapped to LG4 close to four microsatellite markers. Markers TA146 and TR20, linked to QTL2 were revealed to be significantly associated with ascochyta blight resistance at the seedling stage in this half-sib population. The markers linked to these QTLs can further be utilized in marker-assisted breeding for ascochyta blight resistance in chickpea (Kottapalli et al. 2009).

4.5 Family: Brassicaceae

4.5.1 Brassica

Cytoplasmic male sterility and its corresponding nuclear fertility restorer genes, *Rfo*, were introgressed from radish to *Brassica* species, which were extensively utilized in developing canola hybrid seed. Sequence alignment of genomic clones of *Rfo* from a canola restorer line R2000, and a non-restorer line Nexera 705 revealed three homologous sequences of *Rfo*. Based on sequence polymorphisms between the restorer and non-restorer lines, *Rfo* allele-specific PCR markers were developed. One of the allele-specific markers was useful for selecting *Rfo* alleles during marker-assisted introgression in canola hybrid development (Hu et al. 2008).

A single base change in the *Bn-FAE1.1* gene in the A-genome and a two-base deletion in the *Bn-FAE1.2* gene in the C-genome virtually eliminate erucic acid from canola. The single base change in the *Bn- FAE1.1* gene was detected as a single nucleotide polymorphism marker, while the two base deletions in the *Bn-FAE1.2* gene were detected as a SCAR marker. These molecular markers have been employed in marker-assisted breeding of canola/rapeseed (Rahman et al. 2008c).

Turnip yellows virus which is aphid transmitted has become a serious pathogen in many rapeseed (*Brassica napus* L.) growing areas. To get comprehensive information on the genetics of *Turnip yellows virus* resistance derived from the resynthesised *B. napus* line 'R54' and to develop closely linked markers 3-year' field trials were conducted. Bulked-segregant marker analysis identified two closely linked microsatellite markers along with six closely linked and three co-segregating AFLP markers. Two AFLP markers were further converted into co-dominant sequence tagged site markers, making possible the efficient marker-based selection for *Turnip yellows virus* resistance (Juergens et al. 2010).

4.6 Family: Cucurbitaceae

4.6.1 Cucumber

Application of MAS breeding in cucumber (*Cucumis sativus*) has great potential to increase selection efficiency for improving yield components. DNA markers associated with yield components were identified and were utilized in MAS during backcross breeding (Fazio et al. 2003a, b; Fan et al. 2006). Markers utilized for MAS were linked to QTLs for earliness, gynoecy, length to diameter ratio, and multiple lateral branching. Phenotypic selection improved multiple lateral branching and length to diameter ratio and MAS continued improvement of these traits as well as gynoecy. Recently, using four cucumber populations, Robbins and Staub (2009) found both MAS and phenotypic selection to be useful for multi-trait improvement, but their effectiveness depended upon traits and populations under selection. Generally, phenotypic selection was most effective for gynoecy, earliness, and fruit length to diameter ratio, while MAS was effective for multiple lateral branching and increased yield (fruit per plant).

Warty fruit is one of the most important external quality traits related to the market values of cucumber. A single dominant gene, *Tu* (Tuberculate fruit), has been shown to be determinant of the warty fruit trait. Zhang et al. (2010) developed an F_2 population from the cross of S06 × S52 and further utilised for the mapping of the *Tu*/*tu* locus. Bulked segregant analysis was combined with the sequence-related amplified polymorphism and microsatellite markers, consequently 15 markers (nine SRAPs and six microsatellite markers) linked to the *Tu*/*tu* locus were identified. Three markers closely linked to the *Tu*/*tu* locus were successfully converted into SCARs. The *Tu*/*tu* locus was mapped between the co-dominant microsatellite marker SSR16203 and the SCAR marker C_SC933, at a genetic distance of 1.4 and 5.9 cM, respectively, locating the *Tu*/*tu* locus on cucumber chr-5. The C_SC69 and C_SC24 markers were validated with 62 cucumber lines of diverse origins, showing that the two SCAR markers can be used for MAS of the warty fruit trait in cucumber breeding. The knowledge provided in this study can further facilitate the map-based cloning of the *Tu*/*tu* gene.

5 Conclusion

Recent advances in DNA marker assays set the stage for further invigorating and streamlining MAS for plants containing many traits of interest. However, there remain numerous factors which hinder the speed of MAS for recovering polygenic traits, including the unit and capital costs of high throughput genotyping systems, and prolonged and labor intensive methods for identification of marker-trait associations. Further technological innovations coupled with continually-improving automation are still needed to fully exploit the potential of MAS. High-throughput SNP detection systems may have a great influence on future mapping studies and marker assisted-based breeding. Recent advances in DNA sequencing and SNP genotyping promise to streamline new association-based approaches to QTL mapping and quantitative trait nucleotide (QTN), expediting the possibilities of (a) identifying functional variants directly in genes (gene based markers) and not at anonymous markers and (b) whole genome scans. Both approaches rely on the detection of linkage disequilibrium (LD - nonrandom association between alleles at linked loci) and take advantage of recombination events accumulated over many generations. Similarly, QTL meta-analyses, integrating information for one trait from different populations, and mapping QTLs on multiparental populations, hold promise for reducing the gap between marker-based QTL discovery and the practical application of MAS in plant breeding.

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Phytoremediation Techniques for Pesticide Contaminations

Sophie Pascal-Lorber and François Laurent

Abstract Since 1940 the use of synthetic pesticides has led to considerable progress in agriculture and human health. In particular synthetic pesticides were used to protect crops and to fight against disease vectors. As a result it has been possible to feed most of the world population by increasing yields. Beside the beneficial effects for farmers by making their work easier and reducing harvest losses; and benefial effects for humanity by providing abundant food with improved sanitary quality, the intensive use of pesticides has given rise to serious health issues. Indeed pesticides can be very toxic and are responsible of farming diseases such as cancers and neurodegenerative diseases. Besides, with the increase of their efficiency and their selectivity, pesticides become also more and more expensive for farmers. However, in developed countries, there is a rapid change from subsistence farming to intensive farming, which is able to feed more people.

In the past the regulatory framework for pesticide use was less restricting and this led to cases of abuse. In addition, our societies were less aware of the risks of pesticide use for the environment. A major issue is the persistence of pesticides in soils and waters. Indeed pesticides are biocides. Their lack of selectivity could lead to an important risk for living organisms and humans by contamination of drinking water and food. The presence of these biocides or their metabolites in soil, water, plants and even the atmosphere, together with their potential pharmacodynamic properties, can have harmful effects on the environment and on human health. In countries belonging to the European Union, regulations aim to reduce risks at the lowest level, but it is not the case everywhere. Some problems should now be overcome.

Phytoremediation can reduce pollution and decrease the impact of pesticides on the environment. Two examples of substances are discussed in this review to illustrate the risk for the environment and remediation by plants to reduce it. First, the review focused on 1,1,1-trichloro-2,2,bis(*p*-chlorophenyl)ethane (DDT),

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an organochlorine insecticide used with a large success against human disease vectors or in crop protection against some coleopterans such as potato beetles. Its intensive use had contaminated huge areas in the world. Now, it is classified as a persistent organic pollutant (POP), due to its too slow degradation. Plants and associated microorganisms can degrade DDT but metabolites, dichlorodiphenyldichloroethylen (DDE), and dichlorodiphenyldichloroethan (DDD) are of identical persistence. The uptake by plants is very weak, and plant use could not resolve the DDT pollution. The second example is atrazine, an herbicide of the *s*-triazine group. It was largely used in crops such as maize. Now, atrazine and some metabolites are mainly pollutants of hydraulic networks. It is suspected to be an endocrine disruptor. Plants can help to reduce atrazine pollution by accelerating its microbial degradation but some degradative compounds, deethylatrazine (DEA) or deisopropylatrazine (DIA), polluted also water. However, plants could be useful to reduce water pollution because they can reduce run-off of atrazine derivates. Both examples showed the direct action of plants on pesticides by their capacity to take up, accumulate or detoxify organic substances or by their indirect action by stimulation of soil microbial activity in the breakdown of organic compounds.

The use of plants is then presented in the form of examples describing their capacity to prevent pesticide pollution and the use of buffer zones between fields and hydraulic networks. The efficiency of vegetative filter strips (VFS) to protect water from pesticide run-off contamination leads the authorities to require them in good farming practice. Plants could be also used in the depuration of farming wastes. Macrophyte-planted constructed wetlands are efficient to purify farming wastes but their setting is critical.

The variety of contaminated biotopes, as the number of pesticides to depurate, is large. This means that the plant choice must be done among many plants. High variability of plant tolerance does make choice more difficult. Three types of plants are particularly useful: graminae in buffer zones, trees such as poplar or willow in riparian zones or in phytoremediation processes due to large evapotranspiration capacities, and aquatic plants for waste depuration processes. The difficulties to find a polyvalent wild plant, lead to search for new methods to select plants more efficiently. The new genetic engineering technologies are a few developed because they can prove possible to broaden the scope even more. The conclusion consists of a brief glimpse of benefits of the use of plants and their limits.

Keywords Phytoremediation • Pesticides • DDT • Herbicides • Atrazine • Rhizosphere • Metabolism • Vegetative filter strips • Constructed wetlands

Abbreviations

ATZ	Atrazine: 2-chloro-4-(aminoethyl)-6-(aminoisopropyl)-*s*-1,3,5-triazine
BAF	Bioconcentration factor (ratio of total plant concentration vs. soil concentration)
CHC	Clay-humic complex

DEA	Deethylatrazine
DIA	Deisopropylatrazine
DIDA	Didealkylatrazine
HO-A	Hydroxyatrazine
DDD	Dichlorodiphenyldichloroethan
DDE	Dichlorodiphenyldichloroethylen
DDMU	1-Chloro-2,2-bis(*p*-chlorophenyl)ethane
DDT	1,1,1-Trichloro-2,2,bis(*p*-chlorophenyl)ethane
ΣDDT	Sum of DDT and its metabolites
DIMBOA	2,4-Dihydroxy-7-methoxy-1,4-benzoxazin-3-one
GUS	Groundwater Ubiquity Score
GST	Glutathione transferase
HCH	Hexachlorocyclohexane
K_{oc}	The partition coefficient of the compound in organic matter vs. water
OCPs	Organochlorine pesticides
PCP	Pentachlorophenol
RCF	Root concentration factor (ratio of root concentration vs. soil concentration)
TSCF	Transpiration stream concentration factor (ratio from xylem concentration vs. soil concentration)
VFS	Vegetative filter strip.

1 Introduction

The very rapid increase and massive use of chemicals in crop protection and in the management of various parasitic diseases of humans such as malaria and typhus have led to the contamination of farmland and natural areas by persistent agrochemicals (McKone and Ryan 1989). The enthusiasm for these products reflected the beneficial effects for farming and people. Their effectiveness facilitated the work of farmers for example by making manual weeding unnecessary and affording better protection of crops against insect pests and fungal diseases. This meant that populations had more regular and more abundant food supplies with improved sanitary quality. The use of these compounds allowed a rapid, effective response to a problem of human health or of the durability of farming. Even if there have been situations of abuse, agrochemicals have reduced certain difficulties in food crop farming.

Furthermore, with the exception of subsistence farming, no farming system has been able to maintain economically profitable agriculture without measures to protect against pests. It is probable that so-called organic farming systems do not have the capacity to provide sufficient food for the entire population of the world. Thus no developed agricultural country does without the use of pesticides, whatever the method used to manage farming.

As a result, during a period in which the environment was merely a secondary preoccupation for our societies, the main concern in farming was to produce foodstuffs in sufficient quantities. The problems involved in the use of pesticides such as the toxicity of compounds for users and risks that their use and dispersal involved for the environment were long underestimated and not taken into consideration (Mackay and Fraser 2000). However, these problems have been a major issue for our developed societies for some time. The two main reasons for concern as regards to these substances are their dispersal in the environment via water (run-off and infiltration) and via air (volatility of the compounds and dispersal by polluted soil particles) together with the persistence of some of them.

Two substances are emblematic examples of this: atrazine and 1,1,1-trichloro-2,2,bis(*p*-chlorophenyl)ethane (DDT). The latter was the main insecticide used on a large scale in farming and forestry and also for the control of mosquito vectors of malaria and typhus. After a few years, it was dispersed over the whole planet, including the poles (Furgal et al. 2003). Its weak biodegradation makes it persistent in the environment, with a half-life estimated at several decades (Crowe and Smith 2007). Furthermore, it accumulates in the adipose tissue of animals exposed to it. These observations led to fear of serious risk to fauna -especially birds- and to its banning in the developed countries, even for fighting malaria. However, high levels are still found tens of years after it was forbidden in these countries.

Atrazine, a more recent herbicide used extensively in maize growing and along lines of communication (especially railways), is found in aquatic environments after leaching from the soil. It is suspected of causing endocrinal disturbances, especially in batrachians (Hayes et al. 2002) and has been forbidden in many countries for this reason. However, it is still found in watercourses after being banned for several years. Movement in aquatic environments is the main cause of contamination by pesticides as inflow by run-off is continuous (Klöppel et al. 1997).

Substances referred to as ‘persistent’ are therefore currently forbidden in agriculture. However, contamination by them must be remediated. Secondly, even though the substances currently used are less persistent, there is still a risk of dispersion and the non-agricultural environment should be protected from these new compounds.

As a result, the development of sustainable agriculture requires first the restoration of the quality of the environment by eliminating the pesticide contamination, secondly the elimination of initial pollution by limiting use to what is strictly necessary and by creating barriers between the application site, fields, and its surroundings, no crop biotopes. This review describes the facilities used to implement these rehabilitation procedures and to protect environments in which plants form the main remediation agents.

2 Environmental Pollution

2.1 Organochlorine Pesticides (OCPs)

Organochlorines pesticides, such as DDT, lindane or chlordane, display persistence in the environment and strong bioaccumulation in organisms and are hence classified as persistent organic pollutants (POPs) (annexe A, Stockolm convention, 2001), compounds for which methods to remediate the environment must be found in addition to a ban on their use (Turusov et al. 2002; Wania and Mackay 1996; Gonzalez et al. 2005). Historically, DDT is the first pesticide pointed out for an environmental risk, as the causal agent of the decrease of bird population since 1945. DDT was an insecticide used at massive doses against mosquitoes, vectors of some diseases such as malaria. Now, it is widely dispersed in the environment. The remanence of DDT, with a half-life superior to several ten of years, results from its slow degradation by soil microorganisms. Metabolism does not efficiently contribute to its disappearance because the major metabolites, DDE (dichlorodiphenyldichloroethylen) and DDD (dichlorodiphenyldichloroethan) have the same physico-chemical properties and breakdown resistance than DDT (Fig. 1). Natural decrease of these compounds, that is to say natural remediation, by the bacterial flora already present in environments is therefore not effective. So, DDT and metabolites together are considerate as "total DDT" (Σ DDT). The compounds are strongly lipophilic, with log K_{ow} values between 5.5 and 6.9. They thus strongly adsorb on soil particles. Furthermore, the phenomenon is enhanced by alternate drying and wetting phases, a weathering phenomenon that results in decreased bioavailability of hydrophobic compounds for plants and animals in time (Lunney et al. 2004). Σ DDT concentrations magnified in food chain and these lipophilic compounds are stored in body fat. In birds, the main effect, eggshell thinning is due to DDE but the mechanism is not elucidated. Σ DDT is toxic for insects but also for aquatic animals. For mammals and humans, they are less toxic but they are given as endocrine disruptors

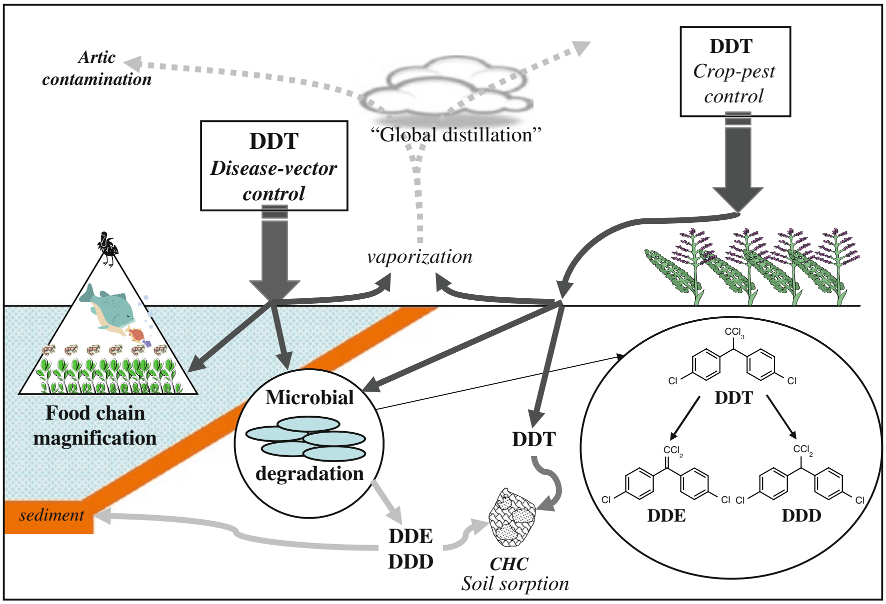

Fig. 1 Scheme showing the distribution of DDT from its use -pest control or disease-vector control- to the global environmental contamination and the two main impacts: the fate in soil with microbial degradation to persistent metabolites, DDE, DDD, and its bioconcentration along food chains

and as probable carcinogens (EPA class B2) although some data was debatable (Rogan and Chen 2005). DDT is an emblematic compound of the organochlorine pesticide contamination but other OCPs, lindane, hexachlorocyclohexane (HCH), chlordane, or chlordecone for example exhibit a similar persistence in the environment and they are listed on the annexe A of the Stockholm convention (2001).

In plants, these compounds tend to be adsorbed on root systems and are very weakly taken up. Several studies have therefore focused on the use of plants to attempt to reduce concentrations in soils and hence the impact on the environment. All land and aquatic (water, sediments) environments are contaminated and studies have been performed on both land and aquatic plants (Tao et al. 2005).

Plants have a direct effect on the soil concentrations of OCPs. In sediments contaminated by DDT and chlordane, in which giant bulrush (*Schoenoplectus californicus*) grew, analysis of the rhizospheric soil fraction revealed a decrease in OCP concentrations in comparison with a non rhizospheric fraction (Miglioranza et al. 2004). Calvelo-Pereira et al. (2006) also found a substantial decrease in HCH concentration in the rhizosphere. The root system caused uneven distribution of contaminants in the soil, with less contamination of the rhizosphere in comparison with the level in unplanted soil. Thus, in spite of their adsorption on sediment and organic matter, OCPs can be available to the plant. However, the root concentration factor (RCF: ratio of root concentration vs. soil concentration) of this compound is fairly similar to that calculated according to their physicochemical constants. For example, β-HCH was measured at 0.35 in artichoke (*Cinara scolymus*) when the calculated value was 0.32, indicating weak bioaccumulation in these plants (Calvelo-Pereira et al. 2008). Other mechanisms for plant polluted-soil interaction can be evocated. The root system may increase gas exchanges and hence the volatilization of HCH or increase water movements, resulting in the movement of contamination to another environment. Root exudates are thought to also contribute to an increase in its solubility in water.

The hydrophobicity of these compounds also limits their translocation in plants. In common reed (*Phragmites australis)*, the ratio between the shoot concentration and the root concentration was lower than 0.75 for DDT (Chu et al. 2006). Products of the breakdown of DDT, DDE, DDD and 1-chloro-2,2-bis(*p*-chlorophenyl)ethene (DDMU) displayed a similar adsorption and translocation profile. Only 20% of root concentration was available for the translocation of DDT to shoots (Chu et al. 2006). The largest fraction of these hydrophobic molecules was only adsorbed on the hydrophobic structures of the roots. The various OCPs generally possess a large number of isomers, for example o,p′-DDT, p,p′-DDT and o,o′-DDT, or α-, β-, γ- and δ-HCH in HCH whose isomer γ, the most potent isomer, is known as lindane. Their accumulation in shoots depended also on the isomer. Hence in common reed, o,p′-DDT was absorbed more rapidly than the isomer p,p′-DDT (Chu et al. 2006). The selective accumulation process of o,p′-DDT would result from its greater hydrophobicity. The isomer feature then operated in the opposite direction as the most hydrophilic compounds were better transferred to shoots: the RCF is 0.35 and 0.24 for β-HCH and α-HCH and log K_{ow} values are 4.15 and 3.94, respectively. By contrast, the TSCF (TSCF = ratio from xylem concentration vs. soil concentration) of β-HCH is smaller than that of α-HCH (Shimizu et al. 2005. There does not appear to be a physiological mechanism enhancing the preferential accumulation (Abhilash et al. 2008). The possibility that this difference may reflect local isomers in the soil following redistribution according to volatility and lipophily cannot be ruled out. However, White et al. (2002) demonstrated the existence of enantioselective processes of technical chlordane, a mixture of α−(*cis*)chlordane, γ-(*trans*) chlordane and oxychlordane (*trans*-nonachlor), accumulation in various tissues of zucchini whereas in contrast translocation in the soil is non-enantioselective.

Most plants display this model of uptake/translocation profile. However, plants of the genus *Cucurbita*, and especially the species *Cucurbita pepo* (courgette and some pumpkins), take up and translocate organochlorine compounds more effectively than other plants. This effectiveness of OCPs absorption by the genus *Cucurbitaceae* was reported by Lichtenstein et al. in 1965 and has been confirmed on many occasions. Courgette and pumpkin both display a bioaccumulation factor (BAF = ratio of total plant concentration vs. soil concentration) greater than 1 for Σ DDT without any isomer selective accumulation (Lunney et al. 2004). Furthermore, the capacity of courgette to translocate DDT residues is greater than that of other plants. Dzantor et al. (2000) compared the absorption of Σ DDT by courgette and the graminae tall fescue and rye grass. They showed that Σ DDT was absorbed by the graminae but with very small translocation into the plant. In contrast, strong concentrations were found in courgette roots and also in the foliage with a translocation factor higher than 1. Courgette is also known for its very effective accumulation of weathered chlordane via a soil-to-plant uptake pathway (Mattina et al. 2000). This is a very significant observation because generally DDT or other OCP contaminations are ageing contamination, consequently with hard difficulty to extract contaminant from soil. The composition of root exudates, in which the proportion and nature of organic acids are different to those of other plants, may explain this greater capacity of courgette absorption by a better dissolution of soil residues of DDT.

Surprisingly, courgette flowers display preferential accumulation of the isomer 2,4-DDE and this pattern is also observed in alfalfa (*Medicago sativa*). That is thought to be the result of a preferential metabolism pathway. DDT metabolism displayed by plants is generally identical to that of the soil microfauna that leads to the formation of DDD, DDE and DDMU. However, these metabolic pathways are not an effective means of breaking down the substance. The parent molecule is not fully broken down and the fate in the environment and the toxicological features of the metabolites display the same profile as DDT (Aigner et al. 1998).

Contamination of environments by DDT and other POPs is long-lasting. The weak degradability of these compounds can explain their high half-life, in addition to a weak availability due to soil adsorption. This shows the requirement for the environment to be protected from these contaminants and also to use alternative methods to natural attenuation to reduce effects of POPs. Degradation by microorganisms of the rhizosphere will not be sufficient since it leads to non degradable metabolites. The weak efficiency of plants to take up POPs limits their use, except for some species that should be deeply investigated.

2.2 Atrazine

Atrazine (2-chloro-4-(aminoethyl)-6-(aminoisopropyl)-*s*-1,3,5-triazine) is a photosynthesis-inhibitor herbicide, used in pre- and post-emergence control of annual broad-leaved weeds and annual grasses mainly in maize and sorghum but also for sugar cane, vines, lemon and banana among other crops. It is also used in non-food crops and at industrial sites such as roads and railways. It was applied intensively during 40 years and several tens of thousands of metric tonnes of atrazine are used every year (30,000 t year^{-1} in US). The substance was found to be a major contaminant of water, polluting both surface water (Garmouna et al. 1998) and underground water (Davoli et al. 1987), resulting in its banning in European Union in 2004. Atrazine is suspected to be an endocrine disruptor, particularly in male frogs (Hayes et al. 2003) and to synergize the amphibian-sensitivity to virus infections, causing the decline of the amphibian population in the world (Forson and Storfer 2006).

The average half-life of atrazine in soil (DT_{50}) is 40 days (Yanze-Kontchou and Gschwind 1995) but depending on the various environments may be as long as 166 weeks, for example in sandy loam soils (Bowmer 1991). The affinity of atrazine for soil organic matter is weak, with a $K_{oc} \sim 100$ cm^3/g (K_{oc} is the partition coefficient of the compound in organic matter vs. water), whence its great mobility in the soil. The association of DT_{50} with K_{oc} give a GUS index (Groundwater Ubiquity Score or $GUS = \log(DT_{50})(4 - \log K_{oc})$ for atrazine greater than 3.56. This shows a strong potential risk of the dispersion of atrazine in aquatic environments (Gustafson 1989). It is confirmed by its strong and persistent presence in aquatic environments. Even though it has been banned since several years in European Union and in spite of its rapid disappearance from the areas sprayed, the repeated use of atrazine has resulted in atrazine and its metabolites being still in aquatic environments.

Atrazine is considered to break down with some difficulty in the soil (Kaufmann and Kearney 1970). Plant cover plays an important role by involving the rhizosphere. The atrazine degradation is very low in bare soil besides vegetated soil (Anderson and Coats 1995). Microorganisms break down atrazine into deethylatrazine (DEA), deisopropylatrazine (DIA) and didealkylatrazine (DIDA) or hydroxyatrazine (HO-A) (Fig. 2). However, the regular use of atrazine in some soils during several years caused the adaptation of the bacterial communities to the degradation of the substance; this resulted in accelerated degradation of the herbicide and complete mineralization (Houot et al. 2000). Accelerated degradation is a metabolic process by which bacteria use atrazine as a single energy-source. Other degradative pathways such as dealkylation are co-metabolism processes in which bacteria use soil organic matter as energy-source. So, the accelerated degradation is very efficient in soils with a low organic matter. Hence, although full mineralization may be effective (Barriuso and Houot 1996), it is generally weak in fields (Lin et al. 2008).

The microbial dechlorination pathway could form a barrier to the dispersion of the herbicide, with HO-A more effectively adsorbed in the clay-humic complex (CHC). In contrast, the dealkylated metabolites are as mobile as atrazine and finally

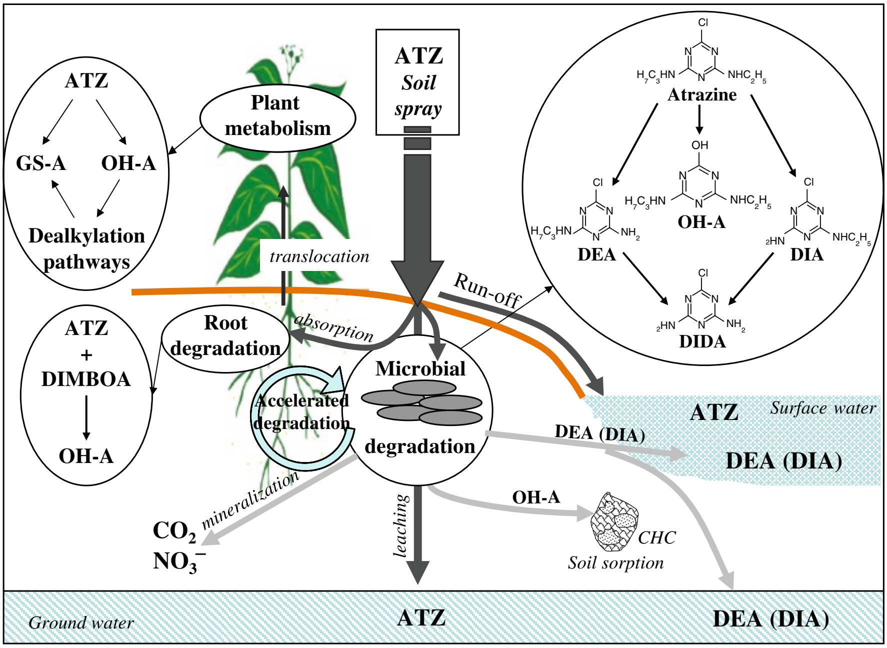

Fig. 2 Scheme of atrazine fate in the environment from fields to aquatic networks that shows the impact of microbial atrazine-degradation on the atrazine-residues transfer towards aquatic biotopes

reach aquatic environments, contributing to "atrazine" aquatic pollution. There is no risk of the bioaccumulation of atrazine or dealkyl-metabolites in food chains, due to its weak hydrophobicity (Lynch et al. 1982). However, the contamination levels observed in water are such as to lead to exposure that appears to be harmful for the environment (Solomon et al. 1996). These concentrations vary from a few tens of $ng\,L^{-1}$ to a few tens of $\mu g\,L^{-1}$ and the half-life is greater than 170 days (Radosevich et al. 1995). The degradation of atrazine, into HO-A and dealkylated metabolites, occurs mainly in sediment (Goswami and Green 1971). The first effects of atrazine in an aquatic environment are related to its herbicidal activity. Changes in CO_2 absorption by algae and in the structure of periphyton communities have been demonstrated with concentration of several $\mu g\,L^{-1}$ (Larsen et al. 1986; Munoz et al. 2001). The exposure of macrophytes to atrazine in the amounts observed in watercourses causes a significant reduction in their biomass, whether this follows acute exposure after a period of strong leaching, for example, or at smaller chronic doses (Cunningham et al. 1984; Kettle et al. 1987). These effects on aquatic plants must have effects on secondary consumers such as aquatic herbivores. In addition, it has been shown that atrazine has a direct effect on aquatic vertebrae and this would appear to be a more serious environmental concern through disturbance to the endocrinal system (Moore and Waring 1998; Hayes et al. 2003).

Due to its K_{ow} of 2.75, atrazine is easily absorbed by roots and then translocated by the xylem flow to shoots. The sensitivity of plant to atrazine results from a difference in the degradation pathways in susceptible and tolerant plants. In the latter, including maize, atrazine is rapidly dechlorinated to HO-A, which is not phytotoxic, in presence of 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA), a substance present naturally in maize roots (Raveton et al. 1997). Nearby this chemical degradation takes place enzymatic degradation. Atrazine may undergo dechlorination via glutathione conjugation or be dealkylated like in microorganisms. Dealkylated metabolites, DEA or DIA, are not entirely devoid of phytotoxicity (Edwards and Owen 1989) and dealkylation pathways are preponderant in susceptible plants.

Only a small fraction of the amount applied (1,000–1,500 g ha^{-1}) is used for the herbicidal activity; the dose required to kill weeds at a plantlet stage is very low. Moreover, the crops such as maize can only take up 10% of the field dosage required to have good treatment efficiency. The rest is dispersed in soil and may reach aquatic compartments. Due to its solubility and degradation, atrazine disappears rapidly from sprayed fields, but the environmental consequences stay several years after the end of its use since it is still detected in water compartments. So, the use of atrazine or pesticides with similar risk for the aquatic environment requires measures to protect water areas.

2.3 DDT/Atrazine Comparison

Work carried out on DDT and atrazine makes it possible to draw up a table showing interaction of plants with the environment and pollution by pesticides (Table 1). It also gives an idea of the possible use of plants either in the remediation of pesticide-contaminated soil -phytoremediation- or by circumventing pollution.

Table 1 Comparison of Characteristics of DDT and Atrazine

		DDT	Atrazine
Physico-chemical characteristics	PM, g mole^{-1}	354	216
	K_{ow}	6.36	2.75
	Sw, mg L^{-1}	3.3 10^{-3}	30
Polluted biotopes		All biotopes	Fields, Water networks
Geo-localisation		Diffuse in global environment	Watersheds
Persistence	Half-life	>10 years	15–100 days
Degradation by microorganisms	Metabolites	DDE, DDD	DEA, DIA, HO-A
	Metabolite persistence	Soil and sediments like DDT	Soil: HO-A Water: Atrazine, DEA, (DIA)
Bioaccumulation		Biomagnification	no
Environmental impacts		Shell thickness	Endocrine disruptor
		Bird decline	Frog decline
Plant fate	Uptake	Low	High
	Phytotoxicity	No	High (except for maize)
	Metabolites	–	HO-A, DEA, DIA

The both examples given above, DDT and atrazine of environmental contamination by pesticides underline two things: first, the quality of environments polluted by persistent pesticides should be restored and, second, environments should be protected at the source from any further pollution. Natural attenuation or microbial degradation is not the solution to remediate environment. So for that, plants could exhibit any efficiency. Although agricultural pollution is not the single cause of contamination of ecosystems by organic pollutants and pesticides particularly, only solutions limiting pesticide pollution in agriculture are described here.

3 Remediation of the Environment

3.1 Remediation Processes

Remediation processes can be physical, chemical, biological or a combination. Common methods of remediation are: incineration, thermal desorption and more recently landfarming, bioremediation, radical oxidative processes and phytoremediation, which will be discussed below (cf 3.2.).

3.1.1 Physico-Chemical Methods

For incineration and thermal desorption, contaminated soils are directly or indirectly heated to vaporize hazardous contaminants that are thereafter burnt, condensed or trapped on granular activated carbon. Physico-chemical methods are rather expensive because soils should be excavated and require a lot of energy. However, these processes have proven to be effective and of low environmental and health risk. The clean soil is generally not returned to the site after treatment and is considered as wastes.

Recent fast-developing processes are photochemical and photocatalytic methods using ultraviolet light, ozone, or hydrogen peroxide alone or in combination with metallic catalysts such as titanium dioxide or iron salts, in Fenton reactions. These methods are generally used to treat water, except some attempts to decontaminate soils by the use of Fenton reactions. They are costly because they require pumping of water, particularly for groundwater.

3.1.2 Biological Methods

Landfarming comes from natural attenuation and involves the controlled application of wastes to a soil or a soil/vegetation system. It is a cheap remediation process but its efficiency, like natural attenuation, is limited.

Bioremediation relies on the enhancement of bacterial growth to improve the degradation of the contaminants. Two strategies can be used, biostimulation that supplies limiting nutrients like nitrogen or carbon to enhance the development of indigenous microorganisms, and bioaugmentation, which provides non indigenous strains able to metabolize the contaminants. These methods can be applied in situ, without soil excavation. However, bioremediation proceeds *ex situ* to homogenize the contaminated soil.

3.2 Phytoremediation

Phytoremediation consists of various processes describing the mechanisms by which plants could reduce the contamination of the soil. These mechanisms have been much-described (Kömives and Gullner 2000; Karthikeyan et al. 2004; Pilon-Smits 2005). Two major processes are involved, depending on whether the pesticide processing takes place outside or within the plant. These processes are (i) rhizodegradation and (ii) phytoextraction (Fig. 3).

3.2.1 Rhizodegradation

In the first case, the root system acts as a support for the soil microflora. The root exudates, consisting of sugars, amino acids, and organic acids, enhance the development of a cortege of bacteria and fungi forming the rhizosphere that leads to an increase of the microbial biomass versus a not planted soil (Bowen and Rovira 1999; Weyens et al. 2009). The effectiveness of bacteria and fungi in the degradation of organic compounds has long been used in remediation processes (Pothuluri and Cerniglia 1994). In phytoremediation, the use of soil microflora in the rhizodegradation process therefore consists in enhancing bacterial or fungal development to

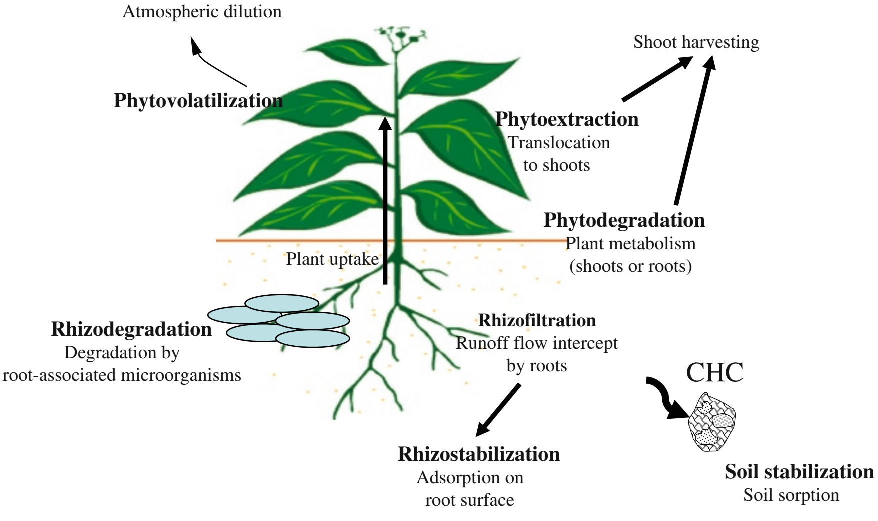

Fig. 3 Various aspects of plant action on the reduction of the pesticide contamination in biotopes

increase the capacity of the soil to break down pesticides (Anderson et al. 1993). Thus, the degradation of pentachlorophenol (PCP) by a strain of *Sphingobium chlorophenolicum* was enhanced in the presence of wheat (Dams et al. 2007). Plants may also modify the structure of the microbial communities involved in breaking down these compounds. Soil used for a maize crop contained a larger number of bacterial strains that mineralized atrazine than bare soil (Alvey and Crowley 1996). From these observations, efficient strains to break down pesticides have been selected and inoculated to soil contaminated by atrazine; nevertheless, the efficiency of the method in fields is very weak because the supremacy of such strains is hard to maintain against the pressure of endogenous bacterial communities (Tucker et al. 1995).

Beside the rhizodegradation, the rhizosphere could play another role in phytoremediation: a rhizostabilization. This mechanism is involved for mineral compounds such as heavy metals (Cunningham et al. 1995). The modification of the oxidoreduction state and the pH of the soil in the rhizosphere by the effect of microorganisms and by root exudates results in the modification of the speciation of metals, which could lead to their precipitation or their binding to organic matter -especially with humic acids- in a more stable, less water-soluble form. This stabilization process does not seem to play an important role for organic compounds. For the latter, stabilization process takes another form: organic compounds such as organochlorines, which are extremely hydrophobic and possess a log K_{ow} greater than 3.5, are adsorbed on the lipophilic structures of the root system. The adsorption can lead to a substantial accumulation on root surfaces and immobilizes the compound at root levels. Here, we talk in terms of phytostabilization, a mechanism that consists in extracting a compound from the soil. This mechanism, like rhizostabilization, is generally considered as reducing pollution and causing few environmental problems (Alexander 1999). However, the process may prove to be transitory. On the death of the plants, the compounds may be released into the environment once again when the roots decompose. To be truly effective, the process should lead to the co-degradation of compounds and roots by the soil microflora, or by the strong binding of these compounds to clay-humic complexes. However, it should be checked by monitoring that stability does not cause fresh subsequent pollution of the site (Mills et al. 2006).

In rhizofiltration or phytopumping, plants have the capacity to evapotranspirate great volumes of water, for example poplar and willow are used to concentrate contaminants close to the root systems. In addition, rhizodegradation or plant uptake could be used. Pollution will be limited to a fewer volume of soil.

3.2.2 Phytoextraction

This second kind of process requires the pesticide uptake by plants. Subsequently, the fate of pesticides within plants determines more precisely the type of phytoremediation process: phytoaccumulation, phytodegradation, phytovolatilization. The ability of plants to take up pesticides with moderate hydrophobicity - log K_{ow}

between 0.5 and 3.5 - is well documented (Briggs et al. 1982). This range is the optimum K_{ow} range to have a good activity/concentration ratio for systemic pesticides. Out of the range, plants also absorb some pesticides, even if the concentrations found within plant do not represent an agronomic interest. Several studies, conducted in particular under hydroponic culture conditions or sometimes using axenic plants, have demonstrated the capacity of plants for rapid remediation of solutions with a high pesticide load (Gao et al. 2000; Flocco et al. 2004). This capacity is related to several parameters; these include the physico-chemical characteristics of the molecule and in particular its lipophily, but also those of the plant chosen, such as the water pumping capacity, the structure and the depth of roots. Once it was absorbed by the plant, the pesticide is immobilized in the roots, transferred to the aerial parts via a translocation mechanism or metabolized. The accumulation in roots is generally inefficient for remediation because, even if the contaminant concentration in soil decreases, it is generally difficult to collect roots to definitively suppress soil contamination. Sometimes, for some plants it is an efficient process, and also for molecules with a high K_{ow}, like ethion ($K_{ow} = 5.07$). The elimination of ethion in water by water hyacinth (*Eichhornia crassipes*) is mainly the result of its capacity for absorbing this insecticide. Only a small percentage of the elimination of the insecticide is the result of microbial degradation. The leaves and roots contribute to accumulation but root concentration is higher than leaf ones. As the root system can form 50% of the biomass of water hyacinth (floating plants) and whole plants (leaves and roots) can be harvested for subsequent elimination of the pesticide (Xia and Ma 2006), root accumulation in hyacinth is a good phytoremediation process. However, accumulation in leaves is preferable because shoots can be easily harvested.

After absorption by roots, a pesticide of medium hydrophobicity can be transferred to the xylem vessels and translocated via the evapotranspiration stream to the shoots, leading to the accumulation of the substance in leaves. For example, more than 85% of imidacloprid, a true xylemien compound, taken up by sunflower (*Helianthus annuus*) shoots is transferred to leaves (Laurent and Rathahao 2003). The accumulation mechanism is effective in reducing concentrations in the soil and referred to as phytoextraction or phytoaccumulation. Like absorption, the shoot accumulation is strongly dependent on the hydrophobicity of the compound with an optimum log K_{ow} around 2 (Briggs et al. 1982). Much study has been devoted to the translocation of pesticides in crop plants, which are being considered for use in phytoremediation because of their generally high growth rates (Vila et al. 2007). This remediation technique is often used with aquatic plants for the decontamination of water. For example, *Typha latifolia* is effective in reducing methyl parathion contamination of water and also of sediment (Amaya-Chavez et al. 2006). Sweet flag (*Acorus gramenius*) and pickerel weed (*Pontederia cordata*) took up simazine, an herbicide of the triazine family and effectively translocated it into the foliage (Wilson et al. 2000). Some part of a pesticide translocated to shoots could be adsorbed in the vessel macromolecules (lignin or cellulose), depending on its lipophily. The use of trees, as poplar or willow, takes into account this mechanism to remediate pollutants in addition to phytopumping. Phytoaccumulation requires harvest of shoots after pesticide accumulation period; thereafter the crops will be processed by burning or composting.

The efficiency of pesticide translocation to leaves can be used to remediate medium polluted by volatile pesticide. The volatilization way is considered like a phytoremediation process by diluting compounds in the atmosphere. In this case, compounds translocated via the evapotranspiration stream to leaves and stomata are expulsed in the atmosphere with plant transpiration. This is tentatively used to remediate water resource polluted by trichloroethane, an industrial solvent, and could be used for some pesticide with a high volatility such as triflutrin.

Phytoaccumulation is seldom an isolated mechanism. Like microflora, plants possess a broad spectrum of enzymes able to metabolize chemicals and the predominance of accumulation or degradation leads to bioaccumulation of the pesticide or not. Lindane is not metabolized by perennial ryegrass (*Lolium perenne* L.), thus leading to its accumulation. In contrast, trifluralin is rapidly metabolized by this plant and no accumulation occurs (Li et al. 2002). Just as ethion is absorbed by water hyacinth, it is then rapidly degraded, without accumulation.

Plants usually metabolize pesticides into more polar compounds which are compartmentalized into vacuoles or as bound residues in cell walls. The metabolism of pesticides in plants has much in common with that of animals and this led Sandermann (1994) to describe plant cells as a ‘green liver’. Metabolism consists of three phases according to the nature of the reactions involved. The first are the primary metabolic reactions (phase I), mainly via oxidation and hydrolysis that convert biologically active chemicals into generally less toxic or less effective compounds. Alkyl- or aryl hydroxylations are the most frequently observed reactions, generally performed by cytochrome P450 enzymes or peroxidases. Sometimes, phase I reactions, particularly hydrolysis, are used to convert agrochemicals (propesticides) to active compounds (pesticides) within plants. Esterification of pesticides is often used to improve penetration through plant cuticle.

Phase II consists in the fixation of endogenous molecules such as amino acids, sugars, glutathione and malonic acid on the primary metabolite. The conjugation is a natural regulation mechanism that enables the plant to increase the water-solubility and mobility of potentially toxic compounds. The most commonly described reactions are glycosylation, generally with a glucose unit, especially when the functional groups –OH, -NH, -SH or –COOH are present, and glutathione conjugation, catalyzed by glutathione transferases (GSTs), involving often the shift of halogen or nitro group on the parent molecule or the molecule scission.

Phase III converts secondary metabolites in more complex soluble conjugates, by addition of some carbohydrate units and malonic acid-sugar conjugation, or in non extractable residues in cell walls. Phase III is often associated to cell compartmentation of tertiary metabolites. Conjugates are stored in the vacuole or excreted to the intercellular space where pesticide moieties are polymerized with cell wall macromolecules. The copolymerization by parietal peroxidase enzymes of pesticide metabolites, generally aromatic or heteroaromatic compounds with hydroxyl, amine or sulphydryl functions, with cinnamic alcohols, lignin precursors, is the main pathway for the formation of these residues (Sandermann et al. 1983). These metabolites are thus stabilized in the structure of the plant. In rape, some atrazine residues are incorporated in cell walls, probably as HO-A (Dupont and Khan 1993). In roots, this pathway may lead to a phytostabilization of pesticides and may prevent the dispersion of pesticide residues after the plant death or shoot harvest. Bound residues are subsequently degraded in the soil at the same time as lignin by lignolytic fungi such as white rot fungi (Trejo-Hernandez et al. 2001). The latter are able to degrade aromatic cycles bound to lignin and are expected to degrade also pesticide residues (Higson 1991). Few compounds can be completely mineralized by plant metabolism. The main reason is that most pesticides contain one or more aromatic cycles that are difficult to open by plant enzymes. Moreover, chemical activation by phase I metabolism and subsequent conjugation lead to accumulation of more hydrosoluble conjugates in vacuoles or cell walls, removing the chemicals from enzymes. If metabolism only detoxifies pesticides and isolates pesticides from the subsequent metabolic steps, it requires plant harvest as for the phytoaccumulation process.

Phytoremediation as described above seems a good process to remediate soil or water contaminated by pesticides. However some limits exist. It is a long process, not able to answer to an urgent situation. Due to phytotoxicity, plants do not support too high pesticide concentrations. The lack of universality of a specific plant toward pesticides due to selectivity of accumulation, metabolization and pesticide tolerance, prevents to remediate multi-pollutions with only one plant species. The "mise en place" of a phytoremediation plan is thus difficult to set up and requires diversifying the plant screening to choose the better plant system.

Moreover, accumulation does not dispense to harvest shoots at the end of the process and to carry out a supplementary treatment to finally destroy pesticides. Generally, the degradation of pesticides in plants requires also plant harvest because plant metabolism is not able to mineralize pesticides and plants accumulate pesticide residues as new chemicals.

Phytoremediation processes have however good advantages by contrast to other techniques because they allow the conservation of the soil cultivability and a stable environment. It requires few incomes except during the installation phase, but after the process could work with a low maintenance. Therefore, this is a process well adapted to some situations and should be carefully examined when a remediation plan is needed.

4 Protection of the Environment

After the question of their efficiency, one of the main current concerns of pesticide users or authorities is to avoid the contamination of water, the final destination of pesticides (Tingle et al. 1997). This consists first of all in using better sprayers and spraying wisely to avoid dispersing chemicals in the environment. Field protection consists in establishing a barrier between the sprayed crops and the aquatic environment. This barrier is often a vegetative filter strip (VFS) lay out along the water network adjoining fields. The second type of protection is the treatment of effluents before their discharge into water network. Plants can be used in fields to run-off or drift interception or at farms for the treatment of unused spraying effluents, which remain in tanks and rinsing water.

4.1 Vegetative Filter Strips (VFS)

The installation of vegetative filter strips consists in setting non cropped zones between crop fields and the water network. The untreated area keeps the treated area remote from the surface water. First, surface water is protected from pesticide drift. Second, the main purpose is to limit the transfer of pesticides in solution or adsorbed on suspended particles in run-off water. VFS are generally planted with perennial grass or wood, or devoted to indigenous plants, or riparian forest. Several studies have demonstrated the effectiveness of the protection afforded by the system (Mersie et al. 1999; Borin et al. 2010). The control of the run-off is often superior to 90%.

Phytofiltration is the main principle of these facilities. The root systems of plants form a barrier to run-off water, increasing the time it takes to reach the watercourse. This allows the redepositing of loaded particles in suspension, better infiltration of water and reducing the leaching. The residual water flowing from the vegetative strip into the water network has a smaller pesticide load than the flows upstream of the strip. The effectiveness of such systems depends on the pesticide of interest, the geopedological field conditions, the width of the strip, the entry flow rate, and also the plant used. Mersie et al. (2003) showed that tall fescue (*Festuca arundinacea*) was more effective than switchgrass (*Panicum virgatum* L.) to reduce the concentration of endosulfan at small flows of runoff. However, there was no difference at higher flows as the effectiveness of the system itself decreased.

Apart from these purely physical phenomena, it is probable that rhizodegradation and phytoaccumulation phenomena are also involved and, together with adsorption on the soil, be factors that contributed to a reduction of pesticide concentrations (Mersie et al. 2003). However, few studies have quantified the remediation role of plants in the fate of pesticides in the environment (Cousins and Mackay 2001) and particularly in VFS.

Increasing the width of the strip can be envisaged to increase VFS effectiveness (De Snoo and De Wit 1998). But this would result in a too large loss of usable agricultural area (Hewitt 2000). Water network can be developed with aquatic plants. Macrophyte role in the abatement of pollution in drainage canals has now been demonstrated (Bennett et al. 2005). The parts of helophytes above the surface of the water intercept spray drift and reduce deposits on the surface of the water (Linders et al. 2000). *Juncus capensis* seems to be particularly effective as it has been reported to reduce the quantity of azinphos-methyl reaching the surface of the water by 75% (Dabrowski et al. 2005). In addition, the submerged part of the plants improves the system by absorbing pesticides in solution in the water

(Hand et al. 2001). This type of development is more effective than making VFS wider. Several countries now include setting of VFS in their good farming practices For example, French regulations require a strip 5 m wide.

4.2 Constructed Wetlands

Protection of the environment also involves the treatment of the contaminated wastes resulting from crop spraying (tank residues, water of sprayers, etc.). These effluents were previously discharged into aquatic environments, leaving the latter to purify contaminants (Williams 2002). In addition to a reduction of effluent volumes, numerous processes are now available for treating them using physico-chemical methods (electro-Fenton oxidation, $Ti0_2$ oxidation) or biological techniques (biobed). The creation of constructed wetlands is an interesting alternative that realizes the natural environmental process in a controlled and restricted area (Moshiri 1993). This procedure is already used to reduce water pollution of mine wastes and in urban sewage treatment. Wastes flow into a constructed wetland planted with macrophytes. These plants were reported to have a pumping effect, reducing the volume of effluent, with contaminants adsorbed on periphyton (Kadlec and Knight 1996). As in VFS, plants filter the water, enhancing the sedimentation of contaminants and serving as a support for the microorganisms that dissipate pesticides (Luckeydoo et al. 2002). Moore et al. (2006) showed the importance of plants to remove most of methyl-parathion in a constructed wetland while only small amounts of this insecticide were trapped in the sediment of a non-planted constructed wetland. Bulrush (*Scirpus validus*) improved the abatement of simazine and metolachlor by 30 to 50% in comparison with bare wetland and 90% depuration efficiency was reached (Stearman et al. 2003). The system had proved its efficiency but its setting is critical to size for the waste volume to treat. It is also critical for the phytotoxicity risk due to herbicide contamination or to the accumulation of some elements such as copper largely used as fungicide on numerous crops.

5 Choice of Plants

5.1 Depuration Capacity

With very rare exceptions, the absorption of organic compounds by plants is a passive phenomenon that depends mainly on the hydrophobicity of the molecules (Briggs et al.. 1982). However, the effectiveness or the success of a phytoremediation plan depends on the plant used. The fate of a chemical in a plant is affected by several characteristics of this plant: the root system structure and physical interaction with the soil, the biochemical composition of roots or exudates, the evapotranspiration capacity of the plant and its metabolic capacity and also its development (Chaudry et al. 2002). Finally for the sustainability of a system, the most important point is plant tolerance to pollutants, even if this depends to a considerable degree on the parameters above. This is essential for herbicides but also applies to other pesticides whose central effect is not the phytotoxicity. Numerous plants have been tested to find those with the best potential. A choice can be made among certain trees in reason of their strong evapotranspiration, large biomass and long lives, among macrophytes for their adaptation to aquatic environments and among cultivated plants -generally large-scale crops- for their rapid growth and the close knowledge of their interactions with pesticides.

The use of trees, or dendroremediation, is mainly conducted using usually hybrid poplar (*Populus* sp.) but other trees such as willow (*Salix* sp.) have also been tested (Volk et al. 2006). Poplar is particularly suitable as it rapidly forms substantial biomass. Its roots can penetrate deeply into the soil and it is considered to be comparatively resistant to various stresses (Bittsanszky et al. 2005). These trees are well suited to soils with comparatively high moisture content and have strong transpiration capacity. This means that they can take up large quantities of water -the ‘pumping’ phenomenon-. They drain a large soil volume, bringing pesticides into the root system zone (Liste and Alexander 2000). As trees are long-lived, absorbed compounds are stored for long periods of time (Trapp et al. 2001). Depending on their hydrophobicity, some pesticides can be adsorbed on the lipophilic structures of xylem vessels and accumulate in trunks and branches. Simonich and Hites (1997) found numerous organochlorine pesticides during the analysis of the bark of trees of various species. Phytoremediation trials with Lombardy black poplar (*Populus nigra italica*) are currently running at a site contaminated by chloroacetanilides. The tree is tolerant to these herbicides as it metabolizes them rapidly into glutathione conjugates. Poplar leaves are particularly rich in glutathione and glutathione transferases (Gullner et al. 2005). Pesticides metabolized into bound residues to cell wall macromolecules are often considered to be biologically stable. Bound residues can subsequently be broken down with the lignin by soil fungi (Ferrey et al. 1994). The long duration of exposure and the large biomass of the trees thus mean that removal of pollutants from soils and substantial storage can be expected.

In contrast, particular attention must be paid to compounds of middle-lipophily. They are translocated to leaves in the evapotranspiration stream. Due to the low mineralization of pesticides by plants, they accumulate in leaves. This results in a ‘futile cycle’ of no interest as regards to remediation and with an increased risk of environmental dispersal. When leaves become senescent or fall down, pesticides or metabolites can be dispersed in the environment once again.

Root systems of trees colonize large soil volumes, sometimes to a great depth (Tsao 2003), and bring high levels of organic carbon to the soil. The microorganism biomass is thus increased in the rhizosphere. A large proportion of pesticide dissipation can then be the result of rhizodegradation. Thus 15% of atrazine can be mineralized to form CO_2 by the rhizosphere of poplars (Nair et al. 1993).

A second category of plants used consists of aquatic species or macrophytes. The choice of these is an obvious one as pollution by pesticides reaches aquatic environments in many cases. Two zones are to be considered: the water, in which the contaminant is in solution or adsorbed on suspended matter; the sediment, in which pollution of longstanding origin is sometimes found. Distribution of pesticides in this biotope, the bioavailability for plants and the part of plant that takes up the compound are very varied. In water, exposure of the plant to pollutants ranges from all parts, including roots, for free-floating aquatic macrophytes such as water hyacinth (*Eicchornia crassipes*) to only the stems or the lower part for emerging macrophytes such as common reed (*Phragmites australis*). Roots and rhizomes are anchored in sediment to varying depths (Brix and Schierup 1989). It is thus probable that the choice of the type of macrophyte will have a considerable impact on the dissipation of pesticides in solution.

Of three free-floating plants, duckweed (*Lemna minor)*, elodea (*Elodea canadensis)* and yellow cabomba (*Cabomba aquatica)*, duckweed seems to have the greatest potential in absorption capacity for depurate a water contaminated by a mixture of three pesticides, dimethomorph, flazasulfuron and copper sulphate (Olette et al. 2008). However, these plants only generate a small amount of biomass that limits their intrinsic potential in contrast with water hyacinth, with its large roots and plant biomass. Water hyacinth has demonstrated its effectiveness in handling organophosphorus pesticides (Xia et al. 2001) but it grows rapidly, carrying a risk of spreading in an environment where it may be undesirable. It is currently considered to be invasive.

Numerous plants can be used and have been tested to remediate polluted sediments (Karthikeyan et al. 2004). Those most commonly used are reed mace (*Typha latifolia*) and reed (*Phragmites* sp.). These plants have roots embedded in sediment, good evapotranspiration capacity and strong growth for rapid colonization of the environment. Reeds have high remediation capacity for nitrogen and phosphorus nutrients, and so they are often planted in wetlands at waste treatment stations (Bragato et al. 2006). *Phragmites australis* has enzymatic potential that also suggests a strong remediation capacity for organic compounds and especially pesticides (Pflugmacher et al. 1999). Reed mace also has good uptake capacity for pesticides such as methyl-parathion (Amaya-Chavez et al. 2006). However, translocation is small for compounds such as DDT, with a translocation factor of less than 1. Twenty percent of root accumulation consists of adsorption on roots (Chu et al. 2006).

In addition to the higher plants, algae can play a role in remediation. The cyanobacteria *Nostoc ellipsosporium* and *Anabaena* degrade lindane and other organic compounds (Kuritz and Wolk 1995). The periphyton that covers the solid surfaces of aquatic biotopes and especially the submerged parts of plants may thus play a role similar to that of the rhizosphere. However, very little is known about this role.

Cultivated plants, especially graminae, are also of interest for phytoremediation purposes. They often display strong vegetative growth and the impact of pesticides is well known. One of the other merits of such plants is that cultivation methods are well known (Dzantor et al. 2000).

The prime use of graminae is in the establishment of vegetative filter strips. The density of stems and the fibrous structure of the root systems efficiently slow run-off flow and enhance the infiltration of this water. However, not all graminae develop in the same way. From the two graminae recommended for vegetative filter strips, the root system of switchgrass (*Panicum virgatum* L.) is more developed than that of tall fescue (*Festuca arundinacea* Schreb) as it has longer, thicker roots. Effectiveness is affected by that. When the run-off flow is small, tall fescue enables better infiltration of endosulfan (Mersie et al. 2003).

Graminae such as ryegrass (*Lolium perenne* L.) display greater remediation potential for PCP than a dicotyledonous such as radish (*Raphanus sativus*) (Lin et al. 2006). As the plants take up very little PCP, the differences would seem to be accounted for by the effect of the roots on the microbial biomass or on the selection of bacterial strains degrading PCP. The development of a denser root system in ryegrass probably results in better exploration of the soil and hence a larger surface area available for the rhizosphere.

The effect of selection exerts by plants on the rhizospheric bacterial flora that degrade pesticides is shown by the effectiveness of some plants in triazine remediation. Soil planted with kikuyu grass (*Pennisetum clandestinum*), a C4 plant, displayed a higher rate of degradation of simazine and atrazine than when it was planted with tall fescue, rye grass or winter onion (*Allium* sp.) (Singh et al. 2004). The phytotoxicity of triazines for C3 plants, unlike the more tolerant C4s, may have a negative effect on the development of the rhizosphere (Karthikeyan et al. 2004).

In addition to graminae, a few trials have been conducted on the use of leguminous such as alfalfa (*Medicago sativa*) and soya (*Glycine max*). Fletcher et al. (1990) showed that soya can be of interest in treating soils contaminated by bromoxynil and other nitrobenzenes. However, few current projects address the use of leguminous, probably because they are more susceptible to environmental stresses than the graminae.

As noted above (cf 2.1), *Cucurbita pepo* - courgettes and pumpkins - have a strong affinity for organochlorine pesticides and could play an interesting role to remediate these compounds, a particularly recalcitrant class of pesticides. The species *Cucurbita pepo* is the only member of the Cucurbitaceae family to display this ability (Lunney et al. 2004). Furthermore, it varies from one subspecies to another and even from one variety to another. White et al. (2003) compared 21 varieties of the subspecies *C. pepo* ssp. *pepo* and *C. pepo* ssp. *texana* and showed that ssp. *pepo* extracted five times more Σ DDT than ssp. *texana* and that ‘Goldrush’, the most effective variety, displayed a BAF greater than nine in roots and stems. This result would appear to be correlated with the exudation of an organic acid with a low molecular weight that in the subspecies *pepo* is the only carrier of phosphorus. This plant is thus a good candidate for the phytoremediation of organochlorines. This shows the importance of choosing plants at both species and varietal levels.

In addition, weak translocation can be harmful for the phytoremediation of a compound. Here again, plants such as the Cucurbitaceae may display considerable merits. The plant cover forms 90% of the total weight of these plants and increases by mass alone the extraction capacity of the compound from the soil. This mechanism has been demonstrated for DDT and chlordane in spite of their low TSCF and it can also be used for other compounds (Mattina et al. 2000).

5.2 Phytotoxicity Problems

The effectiveness of remediation often depends on the plant-pesticide combination. For example, comparison of the effectiveness of the three plants elodea (*Elodea canadensis*), parrot feather (*Myriophyllum aquaticum*) and duckweed (*Spirodela oligorrhiza*) on three organophosphorus compounds (malathion, demeton-S-methyl and crufomate) shows that duckweed is more effective than elodea in accumulating malathion. In contrast, the opposite trend is observed for demeton-S-methyl (Gao et al. 2000). In this case, the differences are caused by differences in absorption and in metabolism.

In other cases, the choice of plant is influenced by the phytotoxicity of the compounds. This is one of the main questions to be evaluated in phytoremediation. Carmo et al. (2008) made this their priority in the development of a plan for the remediation of areas contaminated by picloram, an herbicide. Like the efficiency of remediation, the phytotoxicity depends on the plant-pollutant combination, especially in the case of herbicides. For example, maple trees are susceptible to simazine but not to atrazine. As both triazines act on the same target, differences are probably due to differences in the metabolism (Karthikeyan et al. 2004). Herbicides are basically substances displaying the greatest phytotoxicity, leading to the limitation of their flow into systems. Olette et al. (2008) showed that more than 40 $\mu g\,L^{-1}$ flazasulfuron has a phytotoxic effect, limiting phytoremediation potentials to fairly small flows. Other organic compounds, without intrinsic phytotoxic effect, become phytotoxic, as a result of strong accumulation. This is the case of DDT in tobacco (*Nicotiana tabacum*) (Rosa and Cheng 1973).

The interaction of pesticides with other compounds present in the environment can lead to phytotoxic effects; this notably concerns some metals. Copper is used in large quantities as a fungicide for some crops and can bring out the phytotoxicity of organic compounds. Copper, due its beneficial effect on plant growth, improves PCP dissipation by microorganisms in the rhizosphere but inhibits bacterial activity thus increasing PCP phytotoxicity at high concentrations. Interaction with metals is often complex. For example, lead causes a change in the absorption of atrazine by rice; the ratio of atrazine to Pb^{2+} may cause a decrease or, in contrast, an increase in absorption (Su and Zhu 2005).

5.3 Transgenic Plants

Progress in biotechnology has enabled the genetic engineering of organisms for some twenty years. More than 70% of the genetic modifications to plants grown in open fields have been aimed at obtaining herbicide-tolerant crop plants. The genes introduced code either for a target protein that is tolerant to an herbicide, or for an enzyme that metabolizes the herbicide (Duke 1996). The potential of these enzymes for the removal of contaminants from the environment was soon anticipated. However, in contrast with the genes introduced in cultivated plants where the exogenous enzyme is relatively specific to a given herbicide, in phytoremediation the genes introduced are aimed more at a lack of specificity. Indeed, the metabolic pathways involving broad spectrum enzymes -cytochrome P450 oxidoreductases (Morant et al. 2003) or GSTs (Pflugmacher et al. 2000)- were targeted for engineering plants. For example, Inui et al. (2001) transferred genes coding human or rodent P450 cytochromes in potato and rice. The co-transfer of genes coding several different human P450 cytochromes, CYP1A1, CYP2B6 and CYP2C19, broadens the spectrum of metabolic activity in rice (Kawagashi et al. 2006). With a few rare exceptions, mammal P450 cytochromes have greater catalytic activities than those of plants. This gives hope for achieving good phytoremediation effectiveness for a broad range of pesticides if they are expressed correctly in the engineered plant (Inui and Ohkawa, 2005). GSTs contribute to the degradation of numerous herbicides in tolerant wild plants. Poplars resistant to chloroacetanilides have been bred by transferring a gene coding a GST (Kömives et al. 2003). These transgenic plants mainly target herbicides. However, more recently, a bacterial enzyme hydrolysing organophosphorus insecticides has been introduced in tobacco and is effective in breaking down these compounds (Wang et al. 2008). Other more specific enzymes have been transferred to some plants to address more targeted contaminants. Several recent reviews describe in greater detail the development of these plants genetically modified for phytoremediation (Eapen et al. 2007; Doty 2008). Now, the main problem concerning these genetically modified plants is the non-acceptance of this technology by people.

6 Conclusion

The persistence in the environment of some organic compounds used for crop protection in farming shows that plant cover alone is not sufficient for the effective natural disappearance of these substances.

However, there are several advantages in the use of plants for controlling pollution by pesticides either to abate pollution in an environment or to prevent it. The most noteworthy include the low cost of the application and maintenance of the procedure in comparison with the other techniques and the conservation of the environment by the remediation technique. A point that should be taken into account is that the process is relatively slow.

The development of planted zones on farms -vegetated filter strips or wetlands- is the most pertinent protective approach as this strongly reduces discharge of pesticides into the environment.

The effectiveness of such systems with regard to natural environments lies in the possibility for investors to select the most suitable plants or associated bacteria for the organic compounds targeted. However, much research remains to be conducted to optimize these systems. Indeed, most studies are performed with hydroponic crops and this does not cover the phenomena involved in the uptake of pesticides from the soil and hence the true bioavailability of the compounds for plants.

Another important problem is the multiple organic or metallo-organic contaminations of environments, whether simultaneous at polluted sites or sequential in vegetated filter strips. Multiple contaminations require plants that are tolerant to numerous compounds of very varied kinds.

The use of transgenic plants displaying tolerance to several pesticides is a promising alternative in the search for tolerant wild plants. However, public acceptance of this type of plants has not been achieved, especially with regards to plants having incorporated animal genes whose products of expression seem nevertheless stronger and have broader substrate specificity.

The pesticide tolerance, as the selectivity of pesticides, is not unanimously shared by plants. Therefore, the main difficulty for phytotechnologies applied in agriculture is the absence of a universal plant.

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Sustainable Land Use and Agricultural Soil

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Abstract Sustainable land use is the management of the natural environment and the built environment to conserve the resources that help to sustain the current local human population and that of future generations. This review serves three purposes. First, it gives an introduction to the concept of sustainability in relation to land use, assessing what is "unsustainable" and what is "sustainable." The environmental, historical, and social context is described for understanding current land-use practices. But this will not suppress the demand for viable developmental processes and the potential collateral effects in order to avoid resource depletion. Where natural resources exist, exploitation needs to be adjusted to carrying capacity – that is, it must be determined to what degree the environment is capable of absorbing the impact of the development. As agricultural soil is the foundation for nearly all land uses, soil quality stands as a key indicator of sustainable land use. Second, land use and its mismanagement of arable areas by farmers and grazing areas by livestock is addressed as one of the major causes of soil degradation. This result from erosion, decline in fertility, changes in aeration and soil-water content, salinization, or a change in soil flora or fauna. By reflecting the basic functioning capacity of the soil, it is the measure of many potential uses. On the other hand, management policy will have to adapt agriculture to climate change by encouraging flexibility in land use, crop production, and farming systems. In doing so, it is necessary to consider the multifunctional role of agriculture and to strike a versatile balance between economic, environmental, and social functions in different regions and sectors. Also, attention needs to be paid to all issues concerning agricultural strategies in order to mitigate climate change through a reduction in emissions of greenhouse gases,

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by increasing carbon sequestration in agricultural soils and mediating the growth of energy crops as substitutes for fossil fuels. Third, it concludes that sustainable land use in agricultural systems involves readjusting unsuitable land use and promoting the appropriate use of land for sustainable systems. This review discusses some of the fundamental tasks and examines why sustainable land-use practices and innovations need to be adopted, providing a perspective of close collaboration among scientists, land managers, and policymakers.

Keywords Land management • Sustainability • Sustainable agriculture • Soil quality • Climate change

1 Introduction

The landscape is defined as an area perceived by people, which acquires a character as the result of action and interaction of natural and/or human factors (CE 2000). It is recognized as part of the natural, historical, cultural, and scientific heritage. According to McGlade (2004), in the past few decades, landscapes all around the world have undergone severe degradation which has led to dramatic changes in the physical aspect of the earth. Loss of biodiversity, abandonment of agricultural lands, and acceleration of soil degradation are the results of these changes, which are posing threats to environmental security defined by the United Nations as the relative stability of earth's natural ecosystems to withstand human activity. Researchers have developed indicators to study and classify landscape changes (Banko et al. 2003; Olsen et al. 2007). These are parameters that provide information about the state of an environment, thus bearing implications far beyond those directly associated with the value of any single parameter (OECD 2003). Landscape indicators have a crucial function in research and decision-making, contributing practical information concerning the objectives of sustainable development, and can be used at international and national levels (Piorr 2003; OECD 2003; Fry et al. 2009).

Land use according to the definition of Vink (1975) "is any kind of permanent or cyclic human intervention. Land carries ecosystems. Land use is the application of human control, in a relatively systematic manner, to the key elements within the ecosystem, in order to derive benefit from it." Land in agriculture represents soil that has fertility. Water and fertility are not only kinds of land characters, but also the vital elements of the land ecosystem. Thus, the management of land and water in any agricultural pattern and region seeks to satisfy human needs while controlling soil and water for lasting development of agriculture (Montero and Brasa 2005; Bossio et al. 2010).

In this sense, "Sustainable" means enduring and continuing, i.e. enduring and continuing socio-economic development, as well as the resources and environment on which socio-economic growth relies. Therefore, the sustainable agricultural development of a certain region should first manage the sustainable use of land and water, and thus adopt the basic pattern of using and maintaining natural resources, and implement the technical change and mechanism reform to ensure the requirement of nowadays human being and their offspring to farming products (Tait and Morris 2000; Di Pietro 2001; Sattler, et al. 2010). Such endurable development vindicates the resources of land, water, animal and plant genes, and is of no degradation in environment, rational application in technology, survival in economy and acceptable by the human society (Lyson 2002; Bharat et al. 2005; Zhou and Shao 2008).

Van Paassen et al. (2007) views sustainable land use as a complex issue that involves uncertainties about the dynamics of the biophysical system and the social system and is subject to multiple perspectives. The capacity to identify options for sustainable and equitable development depends on the acquisition of knowledge and skills for (1) holistic analysis of the biophysical system dynamics; (2) examination of the multiple positions, perceptions, values, beliefs, and interests of the relevant stakeholders; (3) assessment of the action needed to fill the gap between the desired socio-technical system and the perceived real-world situation. In this context, sustainable land use is the management of the natural and the built environment to conserve the resources needed to sustain the present human population of the area as well as that of future generations.

In industrialised Western society it is sometimes hard to realise how fundamental the land is to our life on earth. The land has to absorb much of our waste and is the catchment and filter for our water (Loehr 1974; Snowdon et al. 1989). It has to supply us with minerals and materials for our agriculture and industry and also provide us with recreation (Williams and Shaw 2009; Angus et al. 2009). However, this land and its resources are finite, as is its capacity to absorb waste and abuse.

Land is not inert material, a stable growing medium, or cache of minerals, but rather a living community upon which all life on earth depends. It is living in the sense that it is the home, above and below ground, to many millions of species. The maintenance of this life is important for its own sake because it is part of a natural system, a complex web of biological and chemical interactions in which a change in one component results in change in many others. Therefore, our management of the living earth is critical because of reactions, including those related to our own home environment. In addition, land and the consequences of its management, wields heavy impact throughout our society: on our food supply, water, air, employment, the quality of our living environment, recreation, and ultimately our very health and survival (Williams and Shaw 2009).

Also, sustainability refers to the longevity of the health of an agricultural land-use system and hence the ability of this system to maintain a productive capacity. The urgent challenge for our world is, therefore, to develop practices which deliver a sustainable and stable global system, one which minimises the consumption of finite resources and minimizes the generation of waste and pollution, one which satisfies the needs of the humans while maintaining the natural world. It is imperative that new land-management systems be developed which, instead of dealing with individual problems in isolation, properly address the far-reaching impact that they have on all these combined critical issues of sustainability (Haberl et al. 2004; Lamberton 2005). Consequently, a key criterion for a healthy ecosystem is that it is sustainable, especially in maintaining healthy soil over time. For many years, soil-conservation policy and law was the main legal area to manage and control soil and land degradation. An important global conventions, treaties, and strategies for sustainable development during the 1990s have been developed, i.e., United Nations Conference on Environment and Development 1992; Convention on the Conservation of Biological Diversity 1992; Commission on Global Governance, etc. These have been implemented variously around the world to reform natural-resource and resource-management laws and policies.

Agricultural land use has the potential to damage or destroy the natural-resource base, thereby threatening future development. Often, the focus on short-term economic gain and the disregard for long-term impacts and needs lead to environmental degradation. Clearly, part of the solution lies in a shift in demands from society, e.g. via changes in diet and lifestyle, just as the agricultural sector has a responsibility to find ways to reduce the negative environmental impact. Agriculture, rooted in the natural-resource base and serving as a major contributor to development, is at the forefront of shaping the concept of sustainable development (WSSD 2002).

Furthermore, natural ecosystems, the components of which are the results of natural selection, are sustainable; most are productive, pest resistant, and nutrient retentive. Thus, they are appropriate models on which to base the design of new systems of land use for different environments (Ewel 1999). In this context, each environment requires a different solution in the quest for land-use systems that are ecologically, socially, economically, and politically sustainable.

The current situation with agriculture is not sustainable because its practice consumes non-renewable environmental resources, especially soil and ancient groundwater (Edmunds 2003; Zentner et al. 2004). A century of petroleum-driven agriculture has yielded some striking mismatches between land use and the environment. The native ecosystems are time-proven survivors, and it is logical to learn from them and imitate their useful traits. Naturally occurring ecosystems are long-term products of evolution and the accommodation of organisms to environment: they change with time, as both environment and biota change, and they run on solar power, thus making them self-sustaining. By contrast, modern agriculture is completely dependent upon fossil energy fuels, machinery, fertilisers, pesticides, and all the industries that support them (Hatfield 1997). Nature's solar powered systems make eminent sense for the future of food production, making the situation even more critical that most agricultural scientists are ill-equipped to take advantage of the knowledge these systems offer.

Land quality has been defined as "the condition and capacity of land, including its soil, climate, topography and biological properties, for purpose of production, conservation, and environmental management" (Pieri et al. 1995). Therefore, land-quality assessment is of prime importance for decisions on sustainable land uses and the conservation of ecosystems of high biodiversity value. In order to maintain the agricultural production potentiality of land resources, the fundamental element is better management of land. This involves identifying land properties and land-use options, understanding current land-use patterns, and appraising economic and ecological benefits for sustainable land use (Dengiz and Baskan 2009). The rational management of land resources represents one of the most urgent and challenging policy issues in many countries (Gustafsson 1986; Mitchell et al. 2004; Tefera and Sterk 2010). It is an issue that cuts across many different policy interests, such as environment, agriculture, rural and regional development, each of which influences and is affected by the nature and problem of land resources.

2 Sustainability

The principle of sustainability has, for experts of many different fields, become the beacon for finding the way out of the growing conflicts between environment and economy. In the clash between land use and conservation, payments for environmental services may be an appropriate approach to encourage and improve sustainable land use [Convention on Biological Diversity (CBD) Art. 10. Sustainable use of components of biological diversity, and Art. 11. Incentive measures in the sense, United Nations, 1993]. In this sense, action requires three types of criteria to be met: (i) social, (ii) economic, and (iii) environmental.

The concept of payments for environmental services, despite its drawbacks, has several advantages that make it a particularly suitable incentive measure. If payment schemes could be designed carefully and were compatible with ecological, economic, and social aspects of sustainability, they could constitute quite a powerful instrument to promote sustainability. Somewhat simplified, this goal requires (i) choosing environmental services based on ecological criteria, (ii) an economic mechanism which ensures efficient pricing of these services, and (iii) a public framework which ensures transparency and implementation of these measures.

In addition, the importance attached to sustainability represents the convergence of a variety of forces reflecting, on the one hand, society's recognition of increasing demands placed upon a finite resource base and rapid changes in the quality of natural resources and, on the other, the political necessity to act with respect to these pressures and changes. Although this concept lacks a uniform definition, general consensus holds that sustainability must be multidimensional, incorporating ecological, social, political, and economic perspectives (Tisdell 1988; Simon 1989; Smit and Brklacich 1989).

The desire for sustainability in land-use decision making, reflects an increasing public concern on the question: can the existing resource base supply a growing range of goods and services demanded of it without quantitative or qualitative declines in one or more of its social, economic, or biophysical functions (WCS 1980; FAO 1984; WCED 1987)? Answering such a question requires not only regional specification of the issues, but also of the approaches that reconcile theory and practice (Yin and Pierce 1993).

In this context, integrated resource management is an approach by which resource planners, interest groups, and communities attempt to share different perceptions of resource values, resolve conflicts over various resource uses, and coordinate a broad range of agencies and institutions (Manning 1986). According to Mitchell (1986), integrated resource management is a comprehensive, systematic, and coordinated approach aimed at achieving the sustainable use of natural resources. One of the necessary conditions for sustainable land use is that numerous constituents and stakeholders must be recognized as well as multiple objectives that the land base serves. While there are numerous obstacles to achieving these goals, including conflicting or nonexistent policy and lack of communication among groups, two factors impede progress. On the one hand, there is a lack of comparative information and, on the other, there is the problem that most methods frequently applied to natural-resource analysis are one-dimensional, ignoring the importance of intersectorial relations (Smit and Brklacich 1989).

Yin and Pierce (1993) developed an integrated research system, based upon systems analysis and mathematical programming modelling, which was created for the purpose of multi-goal and multi-sector land-use assessment. This analysis procedure is purposely kept general and is composed of four main steps, as shown in Fig. 1.

1. The process begins with an identification of goals. In the public sector, the panoply of land-resource goals is the product of the preferences of decision makers at various levels of government and of interest groups, communities, and other stakeholders. These goals could include: (i) sustainability of regional resource production to meet future domestic and export needs; (ii) economic efficiency that may maximize returns or minimize costs; (iii) soil-erosion control in land development; and (iv) general habitat and wetland conservation.
2. Information is required on the quantity, quality, and distribution of the land-resource base. To this end, assessments need to make concerning the capability and/or suitability of the land uses under consideration, within the context of technological and other socio-economic factors that might sway productivity and land use.

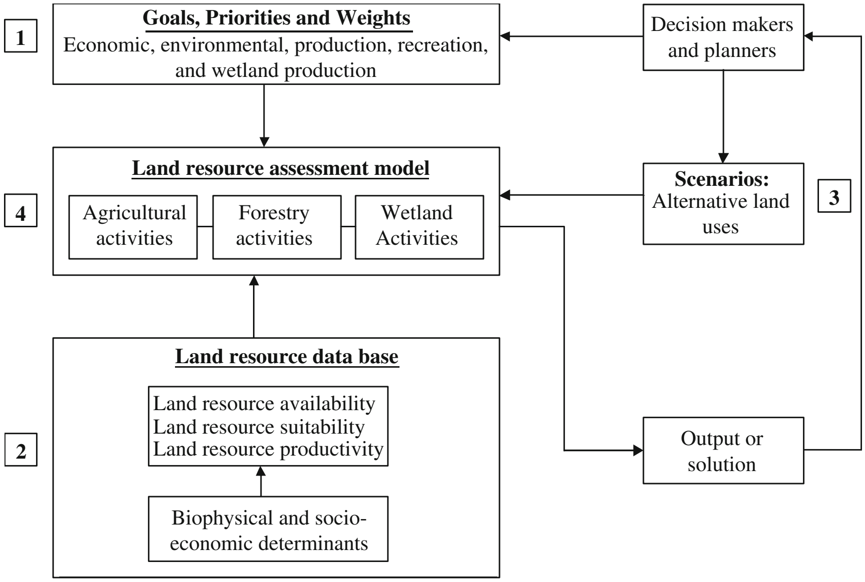

Fig. 1 Research framework for integrated research system by Yin and Pierce (1993)

3. An important ingredient in the exploration and assessment of the impacts of policy change or economic-environmental changes is the specification of scenarios. Scenarios may represent a baseline condition, a continuation of the existing situation, or different assumptions about the growth and distribution of certain land uses.
4. For the evaluation and comparison of these land resource-use alternatives, and for the determination of the implications for various goals, powerful analytical techniques are needed. Goal programming is one technique capable of integrating several objectives and sectors. It can deal with different measurement units and identify trade-offs among alternatives. Unlike linear programming methods, which search for optimal solutions, goal programming seeks a solution that comes as close as possible to the satisfaction of multiple goals (Yin and Pierce 1993).

On the other hand, as an important basis of sustainable development, sustainable land use is inevitably a key topic for researchers, policymakers, and the public. With the definition of the criteria and standards of sustainable land use, evaluation for sustainable land use is the core of research on this issue.

However, in the last few decades, research on evaluation for sustainable land use developed slowly, with an extensive basis on the five principles of sustainable land use proposed by FAO (1993). Other related disciplines are greatly needed to deepen the evaluation.

Land productivity evaluation systems are developed to predict the crop growing potential of lands on the basis of their attributes (Young 1987; McConnell and Quinn 1988; Bedrna 1989; Zhang et al. 2004). In European countries have adopted land evaluation methods based on land and soil parameters (Bouma 2002; De la Rosa et al. 2004; De la Rosa 2005). A soil-evaluation system, where the relative production land potential is quantitatively expressed together with measurements of soil degradation or amelioration with an integrated method, could be developed to express various land quality/land productivity relationships. This approach could help decision makers – together with land users and environmental scientists – to choose profitable and sustainable land-use types and methods at local as well as at regional levels.

Land-use sustainability implies not only the sustainability of a land-use model and biological production on a temporal scale, but also includes the optimisation of land-use patterns on the spatial scale. However, with traditional evaluation for sustainable land use focusing on the social, economic or ecological benefits of regional land use, all can be categorized as the research on the temporal scale, lacking analyses concerning the effects of spatial patterns (Peng et al. 2003). Taking spatial heterogeneity and ecological holism as its theoretical core, landscape ecology can be a great help to create a synthetic evaluation for sustainable land use on temporal as well as spatial scales, with a strong function in the analysis of the spatial patterns of regional land use (Peng et al. 2006; Wang and Yang 1999). However, although many authors have explored the combination between landscape ecology and sustainable land use or land management (Ericksen et al. 2002; Gulinck et al. 2001; Piorr 2003), or have delved further into landscape sustainability (Antrop 2006; Botequillha and

Ahern 2002; Paoletti 1999; Haines 2000), few studies have been conducted directly for evaluation for sustainable land use in terms of landscape ecology, and only Peng et al. (2006) has proposed a framework of landscape ecological evaluation for sustainable land use by dividing land-use sustainability into three aspects, such as landscape productivity, landscape threatening and landscape stability.

According to the ESA (2006) land use in Europe has changed drastically during the last 50 years, especially in regards to human well-being and economic development, which has unfortunately caused serious environmental problems (EEA 2005). The assessment of the impact inflicted by these land-use changes on sustainability is currently a major challenge for the policy makers and the scientific community. One approach developed to address this challenge is Sustainable Impact Assessment and its application at the policy level. The Impact Assessment guidelines of the European Union (CEC 2005) and the renewed and comprehensive EU Sustainable Development Strategy launched in June 2006 (CEU 2006) certainly represent valuable measures for achieving sustainable development within the territory of Europe.

Probably the newest aspect is that the guidelines clearly state that the Sustainable Impact Assessment should perform a real integration of economic, environmental, and social issues across policy areas. On the one hand, this may give the socio-economic issues additional weight in decision-making and help them to maintain the integrity of the environmental assessment. On the other hand, the Sustainable Impact Assessment appraisal more closely reflects actual policy decision making, and is required by the European Union. Therefore, integrating the two procedures makes sense in terms of efficiency.

2.1 Land-Use Functions

Land-use functions (LUFs) are defined as the private and public goods and services provided by the different land uses, which summarise the most relevant economic, environmental and societal aspects of a certain region (Neville 1993; Verburg et al. 2009; Sterk et al. 2009). Some of the “non-commodity” functions can be considered as externalities or public goods. This definition is consistent with the definition of multi-functionality used by the OECD (2003). Each land-use function is characterised by a set of key indicators that assess the “impact issues” defined in the European Union Impact Assessment Guidelines (CEC 2005).

The land-use functions concept therefore allows translation of the European assessment into an integrated regional-impact assessment, i.e. the individual values of the indicators characterising a region that are derived from the model chain are added in order to assess the impact on the land-use functions. In short, the impact on land use predicted by modelling of policy cases can be measured by changes in a set of key indicators that comprise the land-use functions, and can be summarised in one single value per land-use function. Consequently, the land-use functions express in a compressed way the impact caused by a policy option on the functionalities of the main land uses in a region and deals with the progress from Impact Assessment to Sustainable Impact Assessment (Pérez et al. 2008). The outcomes for sustainability are predicted by comparing the values of the indicators with their corresponding sustainability limits/thresholds and by analysing how the policy option stimulates or hinders the land-use function.

2.2 Evaluation Indexes/Indicators for Sustainable Land Use

The sustainability of land use depends not only on the stabilization of land-use patterns and the optimisation of biological and non-biological productions from land use, but is driven also by human demands, which result in pressure on regional land use (Cornforth 1999; Lefroy et al. 2000; Ghersa et al. 2002; Osinski et al. 2003). In broad terms, the greater the human demands for regional land use are, the higher the aim of sustainable land use is, and the lower the feasibility of sustainable land use will be. Therefore, based on the method of Analytical Hierarchy Process, the application of theories of landscape ecology, the indexing system for evaluating regional sustainable land use, can be constructed from three aspects: landscape productivity, landscape threat, and landscape stability (Peng et al. 2007) (Table 1). The index system will help to reveal the distance between the aim of sustainable land use and the status quo of current land use, and will indicate the potential for achieving the sustainability aim in the temporal scale of human generation.

Landscape productivity reflects the capacity of land production, including biological productivity, economic benefits, and potential yield of land use. The higher landscape productivity, the greater the land production is, and the higher the possibility to achieve sustainable land use.

Table 1 Indexes for evaluating sustainable land use based on Analytical Hierarchy Process

Evaluation rule (weight)	Evaluation indexes (weight)	
Landscape threatening (0.35)	Population density	x_1 (0.125)
	Land-use degree	x_2 (0.125)
	Cropping index	x_3 (0.100)
Landscape productivity (0.40)	Total production value of industry and agriculture per unit area	x_4 (0.125)
	Yield of crops per unit area	x_5 (0.125)
	Yield of economic crops per unit area	x_6 (0.075)
	Fertilizer use per area	x_7 (0.075)
Landscape stability (0.25)	Landscape diversity	x_8 (0.100)
	Landscape fragmentation	x_9 (0.075)
	Landscape contagion	x_{10} (0.0375)
	Landscape fractal dimension	x_{11} (0.0375)

Landscape threat is the pressure which is imposed on land use through human activities and which reflects human demands for land use. The more that humans demand from land use, the greater the pressure on land use; the higher the aim of sustainable land use, the greater the difficulty to achieve sustainable land use. Three indexes are chosen to evaluate landscape threat: population density, land-use degree, and cropping index. The higher the value of the three indexes is, the higher landscape threat is.

Landscape stability means the ability to maintain the stability of landscape patterns and functions (Skopek et al. 1991a, b). The greater the landscape stability is, the stronger the landscape resistance is against external disturbance, the stronger the landscape resilience is to regain ecological balance after disturbances, and the stronger the possibility is to maintain spatial patterns and landscape functions (Peng et al. 2007). Generally, in medium-developed agricultural landscapes, the increase of landscape heterogeneity is good to maintain landscape stability.

According to landscape ecology, landscape patterns determine landscape functions. Four landscape parameters are chosen to measure the stability of landscape patterns: landscape diversity, landscape fragmentation, landscape contagion, and landscape fractal dimension. The greater the landscape diversity and landscape fractal dimension is, the stronger the landscape stability, landscape fragmentation and landscape contagion have the opposite relationship. Definitions and more explanations on these metrics were given by Gustafson (1998). Consistent with Analytical Hierarchy Process, four judgment matrixes with the level from 1 to 9 are constructed to calculate the weight of indexes, including the rule layer and the index layer (Table 1; Peng et al. 2007).

As stated by Forman (1990) and Barrett (1992), the landscape is the most appropriate spatial scale for sustainable environmental planning and management. From research in landscape ecology, it can be concluded that land use and landscape ecology closely correlate with each other. Wang (1993) pointed out that landscape ecology shows strong consistency with the concept of sustainable development, which can be regarded as an important theoretic foundation for sustainable land use.

Research on sustainable land use is effective only when it is conducted on a certain spatial and temporal scale, and the scale of human generation should have precedence over other temporal scales (Peng et al. 2006). Meanwhile, sustainable land use not only indicates the sustainability of land use forms on a temporal scale, but also the optimisation of patterns on a spatial scale. To a certain extent, traditional, social, economic, and environmental research on sustainable land use only took analyses on a temporal scale into account, and lacked the spatial analysis of land-use patterns. Taking spatial patterns as well as ecological correlations into account, landscape ecology is helpful for a synthetic analysis; evaluation, and management of sustainable land use both on spatial and temporal scales. In short, landscape ecology provides a new approach for sustainable-land-use research with a focus on spatial dimensions. Although the common general definition of sustainable development touches upon nearly all areas of ecological, economic, and social development, adequate management rules of resource use including a multifunctional land development have been derived from it (Daly 1990; Pearce and Turner 1990).

The general problem of ecological as well as socio-economic effects due to multifunctional land use and the consecutive decision making reveal the enormous complexity of the issue. To construct a model which represents the most important features of the particular state, the complex ensembles of the different elements in a system, and the multiple webs of actions, reactions, and interactions have to be condensed into an applicable pattern. An approach to reach such a practicable model can be based on indicators (Steiner et al. 2000; Lefroy et al. 2000; Ghersa et al. 2002; Wiggering et al. 2006). These are variables or indices, which represent, integrate, and characterize information embodied in comprehensive data sets (Müller and Wiggering 2003), which are often not directly measurable. Indicators are suitable tools whenever the primary information of an object is too complex to be handled without aggregations. Consequently, indicators should not be established by considering pragmatic arguments alone, but also by referring to an optimal theoretical background. This demand is especially important because in many cases indirect effects, chronic interactions, accumulative reaction chains and complex interaction webs can lead to the most evident consequences for the performance of the particular system processes. Thus, a holistic approach is an important prerequisite for a reliable indication of complex systems with different scales. Opschoor and Reijnders (1991), explicitly described the necessary process on how to derive indicators to characterise the so-called functions of scale limits (Daly 1992).

Broadly, the conceptual approaches can become strictly divided into two underlying strategies: (a) the economic orientation and (b) the ecological orientation (Rennings and Wiggering 1997). Still, a consequent merging of these interest-oriented approaches has taken place only to a minor degree.

Thus, it is important to focus on the need to strengthen the discussion on multifunctional land development and land use. Therefore the socio-economic and ecological perspectives should be brought together for solving, for example, the problems within rural areas, forcing sustainable and a subsequent multifunctional land development.

Multi-functionality within this context necessarily has to draw emphasis on both commodity and non-commodity outputs. This is why economic action is always accompanied by ecological and social issues. Sustainable production schemes at the end depend on the relative prices of commodity and non-commodity outputs. Thus, social utility resulting from different degrees of jointness of production can be an indicator for the degree of multifunctional land use and of sustainable use of resources.

Wiggering et al. (2006) pointed out the importance of the fact that indicators for assessing sustainable land development often focus on either economic or ecologic aspects of landscape use. The concept of multifunctional land use helps merge these two focuses by emphasising the rule that economic action per se is accompanied by ecological utility: commodity outputs (e.g., yields) are paid for in the marketplace, but non-commodity outputs (e.g., landscape aesthetics) so far are public goods with no markets.

On the other hand, according to Di Pietro (2001), the agro-system managing land-use practices at the landscape level, seems to be more ecologically sustainable than the one using an individual organization of agricultural practices at field level, according to the two indicators of ecological sustainability of agricultural land use proposed (contribution of fields' environmental features to land use, and diversity of environmental resources used by farms). Many authors have stressed the question of the appropriate scales for sustainability (Lowrance et al. 1986; Fresco and Kroonenberg 1992; Allen and Hoekstra 1992). Di Pietro (2001) suggested that new and more appropriate levels of organization are needed in order to analyse the management of sustainable relationships between agriculture and the environment. They also pointed out that agricultural policies should shift from the field to the landscape-unit level. The focus on a spatial scale larger than fields or farms shows that a local management level of agricultural policies, including all the stakeholders involved in rural development is necessary in order to ensure ecologically sustainable agricultural land use.

3 Land Use and Soil

Water and wind erosion are degrading forces, often resulting from man-induced effects that have occurred in many places and continue to advance (Lal 1994; Song et al. 2005). Worldwide, human-induced soil degradation has affected 24% of the inhabited land area. About 1.5×10^9 ha of land is cultivated. Of this area, about 12×10^6 ha or 0.8% is destroyed and abandoned every year because of non-sustainable farming practices and natural erosion, which triggers a chain reaction (Fig. 2). Overall, soil is being lost from land areas 10–40 times faster than the rate of soil renewal, imperilling future human food security and environmental quality (Pimentel 2006). Water erosion is responsible for 2/3 of the erosion, and wind erosion 1/3. In terms of soil weight, $7.5–9.3 \times 10^9$ t year^{-1} is eroded worldwide by wind, corresponding to about 5 t ha^{-1} year^{-1} on average. The expected level of erosion in the year 2040 is $45–60 \times 10^9$ t year^{-1}, and an 85% reduction is desired (Rennings and Wiggering 1997). The agricultural sector has a challenge to produce sufficient, more diverse and safe food, fibre products, and feedstocks for biofuel in a sustainable manner. This has to be achieved in an increasingly competitive and globalized economy. Meeting these challenges requires significant changes in the way agriculture and the value chain are organized (Roetter et al. 2007).

Some of the major changes affecting agriculture are: (1) globalization of trade, stimulating rapid expansion of the production of high value agricultural commodities; (2) increasing impact of consumer preferences on agricultural production activities and quality standards; (3) urbanization processes, industrial development and access to information technology, leading to a reduction in cultivated area, especially in the land area for less-remunerative production; and (4) impact of global environmental changes, particularly climate-change-induced risks on decision making, and the increasing societal concern with respect to the conservation and use of biodiversity and agrobiodiversity.

Farmers have traditionally been concerned with keeping their soils in good condition because they understand that soil health has a direct impact on crop performance. Managers need information on dynamic soil properties to test whether

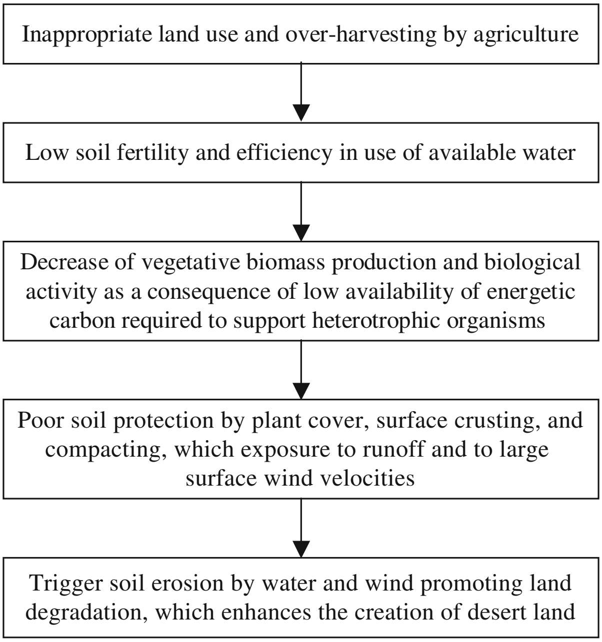

Fig. 2 Impact of inappropriate land use by agriculture

current systems of land use and management are sustainable or whether change is needed. The community, as well as farmers, is concerned as to whether agriculture is sustainable and whether the dynamic soil properties are being degraded by current management practices.

Agricultural land is under severe threat in many parts of the European Union from alternative land uses and inadequate land-use practices (Foley et al. 2005; Lal 2007). At particular sites for housing and industry as well as the expanding transport network, the environmental value of land depreciates, sometimes entirely. Agriculture, by contrast, in many cases preserves land, although negative pressure may be exerted on the soil quality.

The damaging effects on soil fall into three categories:

(i) Physical degradation, such as erosion, desertification, waterlogging, and compaction
(ii) Chemical degradation, such as changes in acidity, salinisation, contamination by pesticides, heavy- metal pollution, etc.
(iii) Biological degradation, including changes to micro-organisms and to the soil organic matter content

In particular, in south-eastern Spain the main agricultural driving forces for soil erosion are unsustainable agricultural practices on sloping lands, such as lack of effective erosion-control measures in production systems including certain types of intensive fruit production and olive trees, soil compaction through the use of heavy machinery, cropping systems that leave soil bare during the rainy season, burning of crop residues, removal of river bank trees and scrub and non-soil-protecting monocultures (De Graaff and Eppink 1999; Fleskens and de Graaff 2008; García 2010; Van Wesemael et al. 2003; Tolon et al. 2010).

At the same time, certain farming systems, such as managed grazing, the presence of hedges and trees, and traditional rotation patterns, may be essential to maintain soil quality. Several agri-environment programmes have the conservation of soil resources as their goal. These include programmes for assuring certain crop rotations and in particular the promotion of organic farming. Programmes also exist to guard against erosion and fire risk, particularly in relation to abandoned land. Afforestation can also make an important contribution to reduce soil erosion.

Despite positive results achieved in areas covered by agri-environmental or afforestation measures, soil erosion is increasing. About 115 million ha in Europe are suffering from water erosion and 42 million ha from wind erosion. Particular problems exist in the Mediterranean region (Montanarella 2008; Table 2).

The problems of soil degradation and soil destruction are caused by the competition between different forms of land use. Therefore, new perceptions and concepts for sustainable land use should be developed, which conform to the constraints of nature. In this context, sustainable land use and soil protection can be defined as the spatial (local or regional) and temporal harmonisation of all the main uses of soil and land, minimising irreversible effects. This is a political rather than a scientific issue. As pointed out above, soil is affected by physical, chemical, and biological degradation, the main effects of which are shown in Table 3. Some agricultural activities contribute to these negative effects. However, it should borne in mind that industry, urbanization, road construction, fire, other human activities and, more generally, demographic pressure and climate changes are also major factors.

The most significant forms of physical degradation of the soil due to agriculture are erosion, desertification, water-logging and compaction. Land-use practices such as deforestation, overgrazing, some agricultural cultivation practices, and removal of vegetative cover or hedgerows can exacerbate these situations (Durán and Rodríguez 2008; Descroix et al. 2008; Fernández et al. 2009; García 2010). The increasing demand for water and sometimes excessive mechanization and ploughing are further causes of such degradation.

Table 2 Human-induced soil erosion in Europe[a] (Million ha)

	Water erosion				
	Light	Moderate	Strong	Extreme	Total
Loss of top soil	18.9	64.7	9.2	-	92.8
Terrain deformation	2.5	16.3	0.6	2.4	21.8
Total	21.4	81.0	9.8	2.4	114.5 (52.3%)
	Wind erosion				
Loss of topsoil	3.2	38.2	-	0.7	42.2
Total	3.2	38.2	-	0.7	42.2 (19.3%)

[a] Includes European part of the former Soviet Union. Source: EEA, European Environmental Agency

Table 3 Estimated areas affected by major soil threats in Europe

Threat[a]	Area affected[b] (Million ha)	Percentage of total European land area
Pesticides	180	19
Nitrates and phosphates	170	18
Water erosion	115	12
Acidification	85	9
Wind erosion	42	4
Soil compaction	33	4
Salinisation	3.8	0.4
Organic-matter loss	3.2	0.3

[a] Different threats can affect the same land area so that numbers cannot be added up

[b] Area covers all land uses

Source: EEA, European Environmental Agency

The following processes characterize chemical degradation: acidification, salinization and contamination by micro-pollutants, such as pesticides and their metabolites, heavy metals and nutrients, i.e. nitrogen and phosphorous (Gzyl 1999; Goudie 2003; Hernández et al. 2003; Arias et al. 2008). However, some pesticides may stay in the soil for some time without serious consequences for the environment. Toxification and eutrophication are two results of pollution.

Related agricultural practices are: over-use of manure and mineral fertilizers, emissions of pollutants by intensive livestock production, spreading of sewage sludge on agricultural soils and the use of pesticides with unintended side-effects (slow degradation).

Finally, in relation to biological degradation, it should be remembered that the quality of the soil is defined primarily by its biological activity, which is affected by humus mineralization and changes in biodiversity. Lowering the organic matter content makes soil more susceptible to compaction, erosion, and other forms of physical degradation. Inappropriate land-use practices, especially in agricultural fields, are most often the reason for this problem. The unintended side effects of pesticide use on soil vitality can explain many changes in biodiversity. However, this occurrence must be considered in conjunction with the forms of degradation described above.

3.1 Soil Quality

Soil quality appears to be an adequate indicator for sustainable land management, being the foundation for nearly all land uses (Parr et al. 1992, 1994; Herrick 2000; Nael et al. 2004; Marzaioli et al. 2010; Cotching and Kidd 2010). Soil quality, by definition, reflects the capacity to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. By reflecting the basic capacity of the soil to function, it involves many potential uses (Dexter 2004a, b, c).

The soil-quality concept evolved throughout the 1990s in response to increased global emphasis on sustainable land use with a holistic focus, emphasizing that sustainable soil management requires more than soil-erosion control. In the mid-1980s, the Canadian Senate Standing Committee on Agriculture prepared a report on soil degradation and revived the concept (Gregorich 1996). Larson and Pierce (1991) defined soil quality as the capacity of a soil to function within the ecosystem boundaries and to interact positively with surrounding ecosystems. They also proposed a quantitative formula for assessing soil quality and suggested that such assessments could help determine how soils responded to various management practices. Assessment tools for indexing soil quality at various scales were pursued to show the multiple functions (i.e. nutrient and water cycling, filtering and buffering of contaminants, decomposition of crop residues and other organic matter sources, and recycling of essential plant nutrients) that soils provide as the foundation for sustainable land management (Karlen et al. 2003). Worldwide research and technology transfer efforts have increased awareness that soil resources have both inherent characteristics determined by their basic soil formation factors and dynamic characteristics influenced by human decisions and management practices.

Early on, Warkentin and Fletcher (1977) suggested developing a soil-quality concept because of the multiple functions of soil resources, e.g. food and fibre production, recreation, and recycling or assimilation of wastes or other by-products. These researchers emphasized that (1) soil resources are constantly being evaluated for many different uses; (2) multiple stakeholder groups are concerned about soil resources; (3) society's priorities and demands on soil resources are changing; and (4) soil resource and land-use decisions are made in a human or institutional context. They also stated that because of inherent differences among soils, there is no single measure that will always be useful for evaluating soil quality.

According to Arshad and Coen (1992) and Haberern (1992), soil quality began to be interpreted as a sensitive and dynamic way to document soil condition, response to management, or resistance to stress imposed by natural forces or human uses.

Traditional soil survey, classification, and interpretation have defined Land Capability Classes, a Story Index, and other Land Inventory and Monitoring indices based primarily on inherent soil properties (Karlen et al. 1997). Each is important and useful for certain applications, but none is the same as indexing dynamic soil quality. The inherent differences among soils, complexity of environments within which soils exist, and the variety of soil- and crop-management practices being used around the world currently preclude establishing a specific rating or value against which all soils can be compared.

Therefore, indexing dynamic soil quality involves the following steps: The first is selecting appropriate soil-quality indicators for the efficient and effective monitoring of critical soil functions (e.g. nutrient cycling; water penetration, retention, and release; supporting plant growth and development) as determined by the specific management goals for which an evaluation is being made (Karlen et al. 2003). These indicators form a minimum data set that can be used to determine how well the critical soil functions associated with each management goal. For each indicator is then scored, often using ranges established by the soil's inherent capability to set the boundaries and by the shape of the scoring function. This step is required so that biological, chemical, and physical indicator measurements with totally different measurement units can be combined, e.g. earthworms per unit area, pH, bulk density, etc. The indicator scoring can be undertaken in a variety of ways (e.g. linear or nonlinear, optimum, more is better, more is worse) depending upon the function. For some management goals the same indicator may be included under different functions and even scored in different ways, i.e. “more is better” for NO_3-N supporting plant growth but “less is better” in relation to leaching process. The unitless values are combined into an overall index of soil quality and can be used to compare effects of different practices on similar soils or temporal trends on the same soil (Karlen et al. 2003). Andrews and Carroll (2001) suggested to understand the complete value of dynamic soil-quality assessment, that it be viewed as one of the components needed to quantify agroecosystem sustainability (Fig. 3).

However, the soil-quality concept has not been universally accepted (Sojka and Upchurch 1999), even though efforts to develop and use soil-quality assessment as a tool to evaluate sustainability are based on a belief that soil scientists must take a more active role in balancing production and environmental quality within agroecosystems (Karlen et al. 2001).

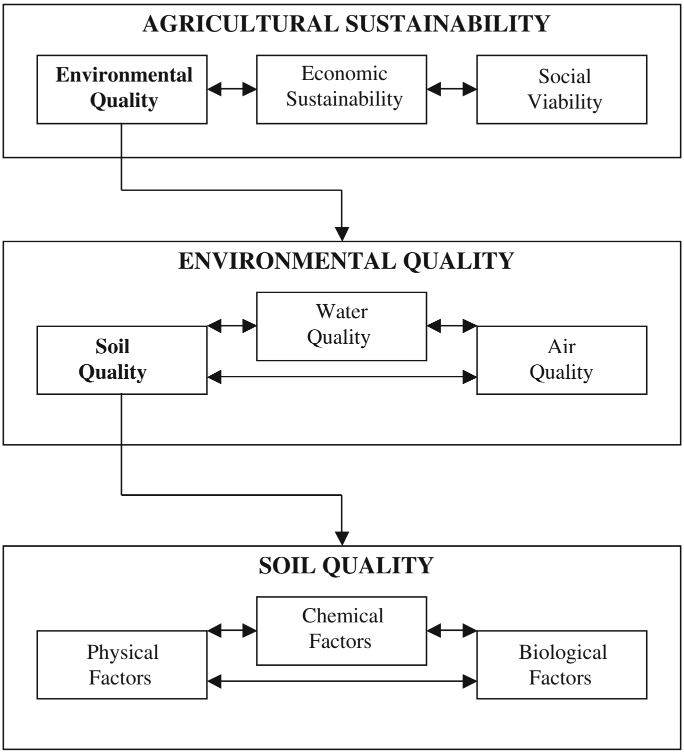

Fig. 3 Hierarchical relationship of soil quality to agricultural sustainability

In this sense, studies conducted in the irrigated central valley of California (Andrews et al. 2002a, b) and the Georgia Piedmont (Andrews and Carroll 2001) demonstrate that soil quality indexing can be a useful tool for assessing sustainability of soil and crop management practices for a wide variety of soils. This is because the nonlinear scoring functions can be easily modified to accommodate soil differences due to their inherent characteristics, e.g. Mollisols in the Midwest of the US typically have higher soil organic-matter levels than Ultisols in the southeast. Furthermore, the relative index of inherent soil quality (Sinclair et al. 1996), criticized by Sojka and Upchurch (1999) as being biased toward US Midwestern Mollisols, is an accurate reflection of the soil-resource potential in the absence of human intervention and external input of energy resources. The lack of correlation between inherent soil quality and economic value of the products produced is expected, because high productivity in areas with low inherent soil quality can be achieved only by creating a highly rated dynamic soil quality, by investing in external energy inputs, and producing high-value crops. Thus, two of the most important factors associated with the soil-quality concept are that soils have both inherent as well as dynamic properties and processes, and that soil-quality assessment must reflect biological, chemical, and physical properties, processes and their interactions (Karlen et al. 2003).

On the other hand, according to Herrick (2000), few land managers have adopted soil quality as an indicator of sustainable land management because there are a number of constraints to adoption. Specifically, this author addresses the following issues:

1. The demonstration of causal relationships between soil quality and ecosystem functions, including biodiversity conservation, biomass production and conservation of soil and water resources. The true calibration of soil quality requires more than merely comparing values across management systems.
2. Increase the power of soil quality indicators to predict response to disturbance. Although there are many indicators that reflect the current capacity of a soil to function, there are few that can predict the capacity of the soil to continue to function under a range of disturbance regimes. Both resistance and resilience need to be considered.
3. The increase in accessibility of monitoring systems to land managers. Many existing systems are too complex, too expensive, or both.
4. Integration of soil quality with other biophysical and socio-economic indicators. Effective early-warning monitoring systems will require not just the inclusion of both biophysical and socio-economic indicators, but also the development of models that incorporate feedback between soil quality and socio-economic conditions and trends.
5. The placing of soil quality in a landscape context. Most ecosystem functions depend on connections through time across different parts of the landscape.

In this context, existing definitions of soil quality and sustainable land management have several elements in common, and an approach is proposed by Bouma (2002) to define a land-quality indicator for sustainable land management focused on agricultural land use which integrates elements of yield, risk, and environmental quality using simulation modelling. Also, socio-economic and political conditions are crucial when defining land quality and sustainable land management, as land qualities have so far implicitly been focused on the field and farm level. Thus, proposed land quality reflects yields, production risks as simulations are made for many years, and soil and water quality associated with the production process.

4 Land Use and Agriculture

According to Buringh (1989) between 11% to 12% of the land surface is generally suitable for food and fiber production, 24% is used for grazing, forests occupy about 31% and the remaining 33% has too many constraints for most uses. The farmland with humans are competing for land and the areas allocated to different land uses reflect the outcome of this competition (Ellison 2006). The world's land area is about 13 thousand million ha, or 29% of the total land surface area of the earth. There is about 3.5×10^9 ha of pasture available worldwide (Seip and Wenstop 2006). Forest land for production of timber, woods and pulp occupy about 0.57 ha per capita, arable land about 0.57 ha per capita, and pasture land used for dairy and cattle about 0.25 ha per capita (Seip and Wenstop 2006).

To increase agricultural production, farmers in almost all agricultural systems have to increase soil fertility, remove weeds, and apply pesticides and water, which clearly has a heavy impact on the environment. The single most important drawback of agricultural use of land is that soils become more exposed to high a risk of water erosion. Also, agriculture affects the environment in different ways: (1) It entails the loss of soil and its fertility in removing nutrients by harvesting crops without replacement (this is called soil mining), and this has several consequences especially in marginal areas; (2) agricultural input causes pollution by pesticides and other chemicals; (3) modern agriculture affects large landscape areas by levelling fields and changing surface structure and soil structure by heavy machinery (land areas from natural habitats to cultivated land), consequently the man-made impact on soil is often the precursor to natural disaster, and (4) land-use for agriculture and farming may conflict with land as protected reserves or land used for recreation.

Farmers often increase the risk of soil erosion and runoff, which pollutes lakes and rivers. Non-sustainable farming practices influence future soil quality, and may cause permanent soil loss and desertification. According to Seip and Wenstop (2006), typical soil-loss rates in the USA are 17 t ha^{-1} $year^{-1}$. The runoff accompanying the erosion is 75 mm $year^{-1}$, 2 t ha^{-1} $year^{-1}$ of organic matter, and 15 kg ha^{-1} $year^{-1}$ available nitrogen. This translates into an overall reduction in crop productivity of 8%, assuming that water and nutrients are not replaced. Replacement costs for nutrients and water amount to US \$196 ha^{-1} $year^{-1}$. The economic cost of soil losses caused by water erosion in the USA has been estimated at \$$7.410 \times 10^9$ annually. Assuming that soil is lost mainly from cropland and pastures (176×10^6 ha in USA), this corresponds to \$44 ha^{-1} $year^{-1}$ or \$34 $capita^{-1}$ $year^{-1}$.

The relationship between agriculture and the natural environment are complex. Agriculture is of vital importance to many societies and is the sector with the most intensive interaction between humans and the environment. Agriculture has, by its very nature, a strong impact on the natural environment and the natural environment sets limits on agricultural production systems. According to De Wit et al. (1987), simply put, changes in agriculture affect the natural environment and vice versa.

Agricultural land use has the potential to damage or destroy the natural resource base, thus undermining future development potentials. It is often the focus on short-term economic gain and disregard of long-term impact and needs that lead to environmental degradation. Clearly, part of the solution lies in a change in demands from society, e.g. via changes in diet and lifestyle, but also the agricultural sector has a responsibility to find ways to reduce the negative environmental impacts. Agriculture, based on natural resources, and serving as a major contributor to development, is at the forefront of shaping the concept of sustainable development (WSSD 2002).

Understanding of the characteristics of soil organic matter and soil nutrients is important for refining agricultural management practices and for improving sustainable land use (Cambardella et al. 1994; Wang et al. 2003). Agricultural practice influences the nutrient balance of agricultural soils, for example by application of fertilizer or manure. In areas with intensive husbandry, manure application may be so massive that runoff and leaching from the soil enriches waters above their tolerance limit (Durán et al. 2004; Rodríguez et al. 2009a). The three most important cycles in relation to soil management and soil sustainability are the cycles of nitrogen (N), phosphorus (P), and organic matter. The first two cycles relate to agriculture, but also to nutrient enrichment of rivers, lakes and forests. The third also relates to the soil as a "fixed enriched nutrient film" for plant nutrition, which also has a risk of transport by erosion and runoff.

Irrigated land area has increased, and the use of purchased inputs, e.g., fertilizers, crop protection agents, and new technologies has grown, leading to increased production per hectare (Fang et al. 2005). Several environmental problems are related to high input levels that result in nutrient and pesticide leaching. The combination of high inputs and advanced technologies clearly has consequences for the sustainability of agro-ecosystems. Overuse and misuse of agro-chemicals works in two ways, it pollutes soil and water needed to sustain production and it directly and indirectly harms human health (Arias et al. 2008; Gheysari et al. 2009; Palacios et al. 2009).

The negative environmental impact of fertilizers has been the subject of research as well as both scientific and public debate for several decades, concentrating mainly on intensive farming systems in the developed world (especially Western Europe and North America); systems which have spread much more recently in tropical regions. Also in this research, a systems approach was followed. Initially, starting with understanding of the effect of the biophysical environment and the role of management at the plot and field scale, the analyses moved up to the farm and regional scales, to include socio-economic aspects of farm-level decision making. Following this approach, trade-offs and possible synergies of management and policy options can be identified.

Agriculture is regularly criticized because of its adverse effects on biological diversity. The threat to biological diversity is twofold. The largest losses of wild biodiversity are those associated with habitat destruction and fragmentation, mainly the result of conversion of natural vegetation for agricultural purposes. Moreover, the environmental impacts of agricultural activities leading to physical, chemical and biological degradation of the environment shrink biodiversity.

However, agriculture also contributes to biodiversity, as the biological diversity in agricultural crop species and varieties and livestock species and breeds is on one hand the result of adaptation to environmental conditions, while economic, social, and cultural factors also play a role in their diversification. This diversity in crop and livestock species, varieties and breeds provides the genetic base for enhancing productivity. However, changes in agricultural production resulted in the cultivation of only high-yielding varieties. The mainstream in biodiversity focuses on the so-called hotspots or regions that accommodate large numbers of species at the risk of extinction (Myers et al. 2000). Because of the low success rate of this approach, efforts have recently been concentrated more on the economic value of biodiversity (Odling 2005).

Global climate change is currently one of the most pressing developmental problems worldwide (Arnell 1999; Hitz and Smith 2004). The specific effects of climate change are local, and they vary for different systems, sectors and regions. However, in a larger sense, climate change has an overarching effect on development. In addition to the urgency of reducing emissions of greenhouse gases to the atmosphere, attention needs to be placed on adapting systems to the changing environmental conditions.

Clearly, agricultural land use will be affected by climate change and variability (Olesen and Bindi 2002; Hitz and Smith 2004; Henseler et al. 2009). Houghton et al. (2001) concluded that in the tropics, yields would decrease with even a small increase in temperature. Semi-arid and arid areas are particularly vulnerable to changes in temperature and rainfall. Shifts in agro-ecological zones will, in some regions, require dramatic changes in production systems. Climate change will also have an indirect effect on crop production via changes in water availability and in susceptibility to and incidence of pests and diseases (Chakraborty et al. 2000; Thomson et al. 2010). High intra- and inter-seasonal variability in food supplies is often the result of unreliable rainfall and insufficient water for crop and livestock production.

Most climate-change studies have focused on either reductions in emissions or response strategies to the adverse effects of climate change and climate variability. Recently, however, the climate-change issue has been subsumed under the larger challenge of sustainable development (Swart et al. 2003; Wilbanks 2003). As a result, climate policies can be more effective when consistently embedded within broader strategies designed to make national and regional development paths more sustainable. Such policies deal with issues such as land-resource management, and energy and water access and affordability (Easterling et al. 2004; Halsnaes and Verhagen 2007).

It is well known that agricultural production affects other land uses, directly via competition for land and water or indirectly via inadequate management, leading to degradation and pollution of soil, water, and the atmosphere. Often the focus on short-term needs or economic gains and the disregard of long-term impacts underlie decisions leading to degradation and pollution; in other cases, the lack of awareness or know-how is to blame. This observation is not new, but so far, solutions and pathways to move to more environmentally friendly production systems have not been very successful. However, by not only focusing on environmental issues but also considering economic and social criteria, a more harmonious picture of problems and possible solutions could emerge.

In addition, it is crucial to know the landscape functions and the influence of agriculture on these functions. In this sense, according to Herrmann and Osinski (1999), there is a need for knowledge of the different assets of landscapes in combination with the potential impact of agriculture (Table 4).

Therefore, it is important to focus on the different potentials of the landscape or the functions it can fulfil. The availability and sensitivity to land-use forms that could endanger the assets, need to be considered.

4.1 Sustainable Soil Management in Drylands

Drylands with its particular climate regimes are not very favourable to crop production (Gupta 1995). Low total rainfall (300–500 mm year^{-1} or less) and high variability in rainfall patterns, present particularly difficult challenges for growing crops (Inanaga et al. 2005). The drylands cover about 54 million km^2 of the globe (UNSO/UNDP 1997) of which semi-arid areas are the most extensive (18%) followed by arid areas (12%), dry sub-humid lands (10%) and hyper-arid lands (7.5%). It bears noting that various land-cover types are found in drylands, ranging from shrubland, forests, and croplands to urbanized settlements.

Since water is the limiting factor for agricultural production, the primary problem is the most effective means of storing the natural precipitation in the soil. Some plants require much less water than others. Others mature early, and in that way become desirable for dryland farming. Rainfed farming as currently practiced in drylands, is a system of low inputs combined with soil- and water-conservation practices and risk-reducing strategies (Martínez et al. 2006; Francia et al. 2006; Durán et al. 2008, 2009). This farming system can be sustainable if practiced properly. Although water shortage is the main limiting factor, successful dryland farming under rainfed conditions should also maintain reasonable practices to minimize other limiting factors such as poor nutrient status, weeds, and biotic stress, which can reduce crop efficiency in using the limited moisture.

Soils in dryland regions have low organic-matter contents due to the characteristically low plant biomass, and are thus predominantly mineral soils. Many of the soils have lower clay content than those in wetter regions. In practice, it is very rare to find soils with ideal texture, reaction, fertility and organic content in drylands. Therefore, there is a need to manage and improve dry soils so that they can perform to their full potential. In sustainable systems, the soil is viewed as a delicate and living

Table 4 Potentials, sensitivities and risks of landscape assets related to agricultural land according to Herrmann and Osinski (1999)

Assets	Landscape potential	Sensitivity	Risk
Soil	Soil fertility	Erodibility and other site conditions (steepness of slopes, rainfall, etc.). Stability of soils	Land use which leads to erosion
	Soil varieties	Trophic levels of soils	Eutrophication
Surface water	Retention areas of water bodies	Amount of rainfall and soil conditions in catchment areas	Land use in catchment areas which increases runoff
	Water quality	Situation of the water body relative to the surrounding land use types	Pollutive and erosive land-use types
Ground water	Water quantity in aquifers	Size of aquifer	Overexploitation of water by farmers/land use
	Water quality	Depth and types of soil water	Intensity of farming (amount of fertilizer and pesticide input)
Habitats for species	Existing habitats	Situation of the habitats in context of the landscape	Land use within habitats and in the adjacent areas which causes change or destruction
	Sites suited for habitat development	Trophic level of sites. Suitability for land use	Land use which disables site-adapted development
Landscapes for recreation	Sets of landscape characteristics suitable for recreation	Open land/forest relationship; grassland/arable land relationship; diversity of land-use types	Land-use changes in sensitive areas

medium that must be protected and nurtured to ensure its long-term productivity and stability. A healthy soil is a key component of sustainability as it produces healthy crops with optimum vigour which are less susceptible to environmental stress. Proper soil management can help prevent some pest problems caused by crop stress or nutrient imbalance. Improved soil and farm management can also significantly increase the amount of water a soil can store for the next growing season.

Soil erosion continues to be a serious threat to crop production in drylands (Parr et al. 1990). Numerous practices have been developed to keep soil in place, which include reducing or eliminating tillage, use of cover crops, plant strips and managing irrigation to reduce runoff. Many environmentalists assume that erosion can be stopped by planting trees. However, this depends on the way the trees are planted and managed, as benefits in soil and water protection do not accrue automatically by having trees on the land (Douglas 1998). It is the litter below the trees rather than the tree canopy itself that provides the bulk of the protection against erosion. If the litter is removed for mulch, fodder, fuel, etc., then the conservation benefits from planting trees are seriously reduced. According to Sanchéz (1987) trees are not always more efficient at protection than annual crops which can provide adequate cover within 30–45 days and pastures within 2–6 months. Lal (1979) pointed out that when mulched, or managed with low tillage, annual crops give the same results for soil loss as do secondary forests.

In the context of good watershed management, well-managed rotational cropping or well-managed pasture may be preferable alternatives to poorly managed forest land (Shaxson 1992). The risk of soil loss by water and wind erosion can also be reduced significantly by protecting the soil surface with at least a 30–35% cover of straw or gravel mulch.

In dryland areas the water received as rain or snow can be easily lost before it can be used by a crop. Water taken up by weeds or lost to evaporation are the two most negative fates of water that must be avoided if precipitation-use efficiency is to be improved. Where economically feasible, irrigation is the most direct means for combating drought conditions and intensifying agricultural production. However, for sustainability, irrigation must be practised in such a way as to avoid such hazards as soil erosion, salinization, leaching and disease infection. Sustainable irrigation must be based on knowledge of the crop, soil properties and the potential evapotranspiration of the specific crop at the site. Supplemental irrigation is defined as the application of a limited amount of water to rainfed crops when precipitation fails to provide the essential moisture for normal plant growth (Oweis et al. 1998, 2000).

Studies at ICARDA (International Center for Agricultural Research in the Dry Areas) showed that two or three irrigations (80–200 mm) increased grain yield in wheat by 36–450%, and produced similar or even higher grain yields than under fully irrigated conditions (Perrier and Salkini 1991). Supplemental irrigation is widely practised in Syria, and in southern and eastern Mediterranean countries. Water harvesting is a broad term describing various methods of collecting runoff from large contributing areas and concentrating it for use in a smaller crop area. Mulching is a method involving dense covering of the soil surface with gravels (Inanaga 2002) or with woody or non-woody plant stem, branch or leaf fragments or residues (Martínez et al. 2006; Francia et al. 2006; Durán et al. 2008, 2009; Rodríguez et al. 2009a, b). It is effective in reducing evapo-transpiration and surface runoff of rain water, thereby increasing its percolation to the soil for use by crops.

Water-saving polymers have also been formulated and manufactured to provide better moisture management capabilities and longer lasting effects on crop performance (Fernández et al. 2001; Ouchi 2001). Polymer crystals are incorporated into the soil preplant or at planting. These crystals absorb moisture and transform into gel-like nuggets of water and nutrients to meet the needs of plants when root-zone conditions turn dry. The polymers expand many times their original size, retaining moisture and water-soluble nutrients until plants need them. However, a major potential limitation to the use of polymers is the high cost.

4.2 Sustainable Soil Management and Climate Change

As environmental quality increasingly deteriorates due to agricultural practices, the importance of protecting and restoring soil resources is being recognized by the world community (Lal 1998, 2001; Barford et al. 2001). The sustainable management of soil received strong support at the Rio Summit in 1992, as well as in Agenda 21 (UNCED 1992), the United Nations Framework Convention on Climate Change (UNFCCC 1992), and the Kyoto Protocol (UNFCCC 1998). These conventions are indicative of recognition by the world community of the strong link between soil degradation and desertification on the one hand, and loss of biodiversity, threats to food security, increases in poverty, and risks of accelerated greenhouse effects and climate change on the other.

The growth of the global population has placed increased strains on agriculture to produce more food--the world population has grown by one billion people in the past 12 years, exceeding six billion in 2000, and is projected to swell to nine billion by 2050 (Brown 2004). More than 90% of this growth has taken place in developing countries, in sharp contrast to Western Europe, North America, and Japan, where the population growth is low or at a standstill. Increasing demand for food has resulted in increased soil disturbance, increased fossil-fuel consumption to produce agricultural products, and increased biomass burning. Therefore, the application of adaptive soil-conservation measures under the effects of climate change is needed.

In this sense, soil organic matter plays a key role in building and sustaining soil fertility, affecting physical, chemical and biological soil properties. Higher temperatures due to climate change will accelerate the turnover rate of organic matter. The effects are likely to be highest during winter, and increased turnover may lead to the build-up of inorganic nitrogen in the soil and greater risk of NO_3 leaching. The overall effect of climate change on soil organic matter levels and NO_3 leaching will depend on how climate change affects soil moisture during the summer season (Leirlos et al. 1999), on the counteracting effect of increased carbon (C) inputs from the growth-enhancing effect of increased atmospheric CO_2, and on increased NO_3 uptake by the vegetation (Ineson et al. 1998a, b). Depending on the current situations this may lead to augmented CO_2 emissions, which probably will be most pronounced from peat soils and also affect the use of these soils for agricultural purposes (Hartig et al. 1997; Chapman and Thurlow 1998). Ineson et al. (1998b) and Kamp et al. (1998) reported that N_2O emissions may also increase under some conditions affected by changes in temperature, soil moisture, and C input. Drier soil conditions will become more vulnerable to wind erosion, especially if winds intensify. Higher evaporation will also exacerbate the risk of soil salinisation in regions where total rainfall is restricted (Yeo 1999). According to Favis and Guerra (1999), an expected increase in rainfall, caused by stronger temperature gradients and more atmospheric moisture, may result in more frequent high-intensity precipitation events, increasing soil erosion.

According to Lal (2004a, b, c) proper soil management has great potential to contribute to C sequestration, since the carbon sink capacity of the world's agricultural and degraded soil is about 50–66% of the historic carbon loss of 42–72 Pg ($1\ \text{Pg} = 10^{15}$ g of C). The C sequestration implies transferring atmospheric CO_2 into long-lived pools and storing it securely so that it is not immediately re-emitted. Soil organic carbon stocks, through the addition of high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, enhance activity and species diversity of soil fauna, and strengthen the mechanism of elemental cycling, as was pointed out by Lal (2004a, b). Proper sustainable land-use practices that improve soil quality through enhancing the SOC stock will become more noticeable, since soil management determines the level of food production, and, to a great extent, the state of the global environment. Thus the current pressure on the land resources of the world is vitally important especially under climate change.

In this sense, soil organic matter, which includes a vast array of carbon compounds originally created by plants, microbes, and other organisms, helps to maintain soil fertility and plays a variety of roles in the nutrient, water, and biological cycles (Tiessen et al. 1994; Reeves 1997). Soil organic matter is also crucial for its normal function of supporting crop growth naturally, providing a place for water, air, and biological ecosystems to exist in the soil.

Many authors (Duff et al. 1995; Mitchell et al. 1996; Reeves 1997) with long-term studies have consistently shown the benefits of manuring, adequate fertilization, and crop rotation for maintaining agricultural productivity by increasing C input into the soil.

Under the effects of climate change on agricultural productivity in Europe, Olesen and Bindi (2002) have estimated that in northern areas the changes may have positive effects on agriculture through introduction of new crop species and varieties, higher crop production and expansion of suitable areas for crop cultivation. Disadvantages may include a greater need for plant protection, the risk of nutrient leaching and the turnover of soil organic matter. In southern areas the disadvantages will predominate. The possible increase in water shortage and extreme weather events may cause lower harvestable yields, higher yield variability and a reduction in suitable areas for traditional crops (Olesen and Bindi 2002). These effects may reinforce the current trends of intensification of agriculture in northern and Western Europe and extension in the Mediterranean and south-eastern parts of Europe.

Thus, policy will have to support the adaptation of European agriculture to climate change by encouraging the flexibility of land use, crop production, farming systems, etc. In doing so, it is necessary to consider the multifunctional role of agriculture, and to strike a variable balance between economic, environmental, and social functions in different European regions. Policy will also need to be concerned with agricultural strategies to mitigate climate change through a reduction in emissions of CH_4 and N_2O, an increase in C sequestration in agricultural soils, and the growing of energy crops to substitute for fossil energy use, as pointed out above. In this context, Cowie et al. (2007) proposed different strategies of land-use change in order to mitigate the effects of climate change.

4.3 Cropland and Soil-Carbon Sequestration

Cultivated soils store great amounts of soil organic carbon, being one of the sinks for atmospheric CO_2. Plant biomass and soils store about 500 Pg and 1,100 Pg C, respectively, on the global scale; C stored in soils is mainly in the form of soil organic matter (IPCC 1996). As for the C dynamics of croplands, crops accumulate carbon, resulting in CO_2 fixation by photosynthesis and C consumption by respiration. Part of the net crop C accumulation is removed through the harvesting process, while other types of crop residues, including litter and roots, remain in the cropland. These crop residues through the mineralization process are decomposed to CO_2 or transformed to organic matter in the soil by microbial agents, which strongly depend on the C:N ratio (Rodríguez et al. 2009b).

One of the major factors in C loss from croplands is soil respiration, including microbial decomposition and root respiration. In this sense, according to Magdoff (1992) the soil respiration rate is influenced by soil type, climatic conditions, amount and quality of soil organic matter input, and soil management. The CH_4 emission from paddy fields is another process of soil-carbon loss, and the leaching of organic carbon, such as root exclusion.

As stated by Weil and Magdoff (2004), the increase of soil organic matter can enhance the diversity of the prokaryote community, as well as biomass. Prokaryotes are an enormous component of the biological carbon pool in the Earth's carbon cycle. Whitman et al. (1998) estimated the number of prokaryotes and the total amount of their cellular carbon on Earth to be $4–6 \times 10^{30}$ cells and 350–550 Pg of C, respectively. Prokaryotes also possess a vast metabolic diversity and, thus, contribute to all aspects of C cycling in agricultural soils.

Wood et al. (2000) pointed out that globally, agricultural soils account for less than one-fourth of the soil organic carbon pool, and organic carbon levels are related to climate, topography, and soil texture. Also, this author reported that soils in the USA, Asia, and Europe are considerably richer in soil organic carbon (12.2, 12.6, and 14.6 kg C m^{-2}, respectively) than in sub-Saharan Africa (7.7 kg C m^{-2}).

There are some difficulties involved with increasing or decreasing soil organic carbon, and continuing on an indefinite basis by using the same soil management or land-use practices. In this sense, Bellamy et al. (2005) found that carbon loss from soils across England and Wales during a 25-year study period (1978–2003) occurred at a mean rate of 0.6% per year, also, the relative rate of C loss increased with soil carbon content and was more than 2% per year in soils with a carbon content greater than 100 g kg^{-1}. These authors considered the relationship between the rate of carbon loss and soil carbon content to be irrespective of land use, concluding that the carbon loss was linked to climate change. By contrast, Schulze and Freibauer (2005) maintain that the land-use factor plays a primary role and climate change a secondary factor.

Agricultural measures are needed for carbon storage in croplands. However, the applicability of these might differ according to the soil type and region. In this sense, according to Follett et al. (2005) some recommended management practices for soil C sequestration in croplands could be as follows: (i) adopting conservation tillage, surface-residue management, and mulch farming; (ii) cultivating crops with deep root systems; (iii) developing and cultivating high-lignin plants, especially in debris and roots; (iv) eliminating summer fallow and incorporating legumes and other appropriate cover crops in rotation; (v) applying animal manure and non-toxic anthropogenic biosoil; (vi) enhancing biological N fixation; and (vii) increasing crop biomass production.

According to Lal (2004d) the rate of increase in soil organic carbon stock, through land-use change and adopting recommended management practices, follows a sigmoidal curve that attains the maximum 5–20 years after the adoption of recommended management practices, and continues until organic carbon attains a new equilibrium. In addition, the soil-management practices directly affect the soil organic carbon pool by changing the carbon balance of input and output of organic carbon. A comparison of soil-management practices that increase soil carbon stocks is shown in Table 5.

Figure 4 depicts a simplified flow diagram of C pools and fluxes in a forest system. The C fluxes enter into biomass through photosynthesis, after which the biomass components go either into soil or to biomass extraction or remain as standing biomass in the vegetation. The C emissions are then emitted back into the atmosphere through the extracted biomass, e.g., firewood, timber, fodder, animal beds, poles, paper and pulp, etc. Some part of the biomass component enters the soil as organic matter, thereby enhancing the soil organic carbon in soil profiles, or decomposes, contributing to the emissions. Therefore, there are different levels of biomass and soil organic carbon under different land uses. Once the changes in land use or extraction of biomass take place, C stocks in biomass and soil are affected with significant implications for C sequestration. At a given point of time, any C pool in Fig. 4 acts as a sink or source, depending on whether the net result of sequestration and emission is positive or negative.

In this context, Upadhyay et al. (2006) concluded that land-use changes and forests/soil degradation are affected mostly by complex interactions of ecological, biophysical, socio-economic, and institutional factors. Also, it is not possible to find unambiguous cause-effect linkages that would have a universal application.

Table 5 Soil-management techniques to improve and increase soil organic matter

Soil management	Positive effects	Negative effects	Additional C stock ($Mg\ C\ ha^{-1}\ year^{-1}$)	Source
No-till	Slightly low level of SOM conversion into humus and improvement of soil aggregation, erosion control, reduced fuel usage	Possible emission of N_2O, possible increased pesticide usage	0.07–0.33	Robertson et al. (2000)
Cover cropping	Increase SOM by recycling plant waste, increase the soil respiration, reduce soil erosion and applied fertilizers to the field	Possible emission of N_2O	0.15–0.25	Lal (2004b, c, d)
Crop rotation	Increase the SOM input and interrupt the pest and disease cycle	None	0.05–0.25	Lal (2004c, d)
Manure application	SOM input with additional plant nutrients and improvement of soil respiration and productivity	If inputs are high the risk of NO_3 leaching and emission of N_2O is important	0.05–0.15	Robertson et al. (2000), Lal (2004c, d)

SOM soil organic matter

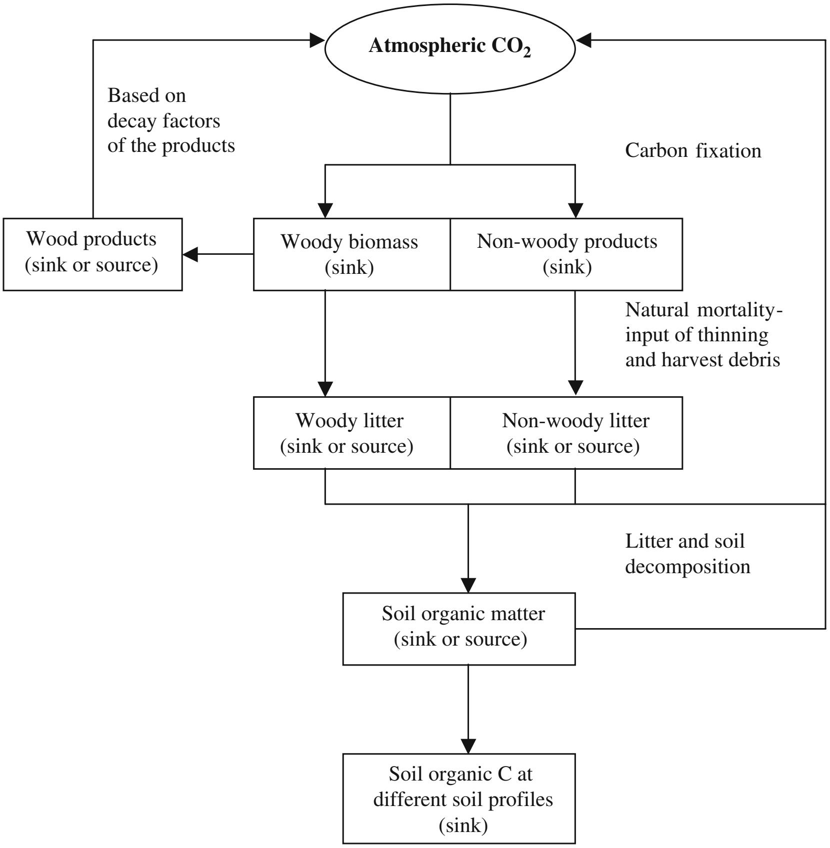

Fig. 4 Carbon pools and fluxes in a land-based ecosystem (*Source*: Cannell 1995)

On the other hand, Oelbermann et al. (2004) reported that agroforestry systems have the potential to sequester atmospheric C in trees and soil while maintaining sustainable productivity, estimating aboveground components to be 2.1×10^9 Mg C year^{-1} in tropical and 1.9×10^9 Mg C year^{-1} in temperate biomes.

4.4 Soil Management for Sustainable Use

The soil management to maximize the benefits from soil organic carbon will require serious compromises in order to achieve agricultural sustainability. Some inappropriate practices such as complete debris removal for seed bed preparation, reducing manure application, single and continuous cropping, and the elimination of winter crops have significantly reduced organic matter input to cropland, and the enhancement of soil respiration by increasing N fertilizer application is resulting in a significant decline in soil organic matter.

The soil organic carbon has become the most important indicator of soil quality under sustainable land use because of its impact on other physical, chemical, and biological indicators of soil quality (Reeves 1997; Bationo and Buerket 2001). Long-term studies have consistently shown the benefit of manure, adequate fertilization, and crop rotation on maintaining agricultural productivity by increasing C input into the soil, as pointed out by Mitchell et al. (1996) and Reeves (1997).

The recent actions of many governments to develop more environmentally friendly farming practices, and the importance of surplus reduction have led to widespread interest in organic farming and environmental conservation farming (Hansen et al. 2001; Wood et al. 2006; Shi-ming and Sauerborn 2006). Under conservation management techniques, traditional agricultural methods are combined with modern farming techniques, while conventional inputs such as synthetic pesticides and fertilizers are excluded or at least reduced (Rigby and Cáceres 2001; Wood et al. 2006). Soil fertility is built up by cover crops, compost, and animal manure. In south-eastern Spain extensive areas cultivated with rainfed tree crops (i.e., olives, almonds, and vines) are mainly confined to hilly marginal lands with shallow soils which are very prone to erosion under traditional soil-management systems but erosion can be significantly reduced by the use of plant strips (i.e., cereals, legumes, and aromatic and medicinal plants) running across the hillslope (Fig. 5). Also, soil erosion could be prevented by planting the taluses of terraces with covers of plants having aromatic, medicinal, and mellipherous properties. This increased the feasibility of making agricultural use of soils on steep slopes.

The organic matter in the soil has many benefits for agroecosystems, and its increase can mitigate some problems associated with soil management systems. According to Miura and Ae (2005), during the fallow season, a fertile soil sometimes causes nitrate (NO_3) leaching into groundwater. Even with organic agriculture, the soil may cause NO_3 leaching, depending on soil management, because it is difficult to synchronize the N mineralization from manure, compost, or crop residues with the crop growth (Rodrígues et al. 2006). Therefore, soil-management strategies for sustainable agriculture should focus not only on increasing soil organic matter, but also on the uptake or storage of soil residual nutrients in order to prevent excess plant nutrients from leaching into the water bodies.

The NO_3 leaching occurs mainly in the rainy period, when there is high precipitation and relatively little evaporation, resulting in downward movement of soil water. According to Rodríguez et al. (2009a), the NO_3 concentration in leachates was often over 10 mg L^{-1}, and the highest concentration was observed in the rainy period in a subtropical production area with over 50 mg L^{-1}, which exceed the concentration limit. Similar findings for high N concentration in leaching waters from orchard terraces with cherimoya trees was reported by Durán et al. (2006). On the other hand, even organic farming may promote excess NO_3 concentration due to the accumulation of soil residual nutrients from long-term organic-matter input in the field.

Reinken (1986), in a 6-year field study, demonstrated that there were no differences between organic and non-organic methods detected in total-N or protein in a number of vegetables and three varieties of apples. The soil management for

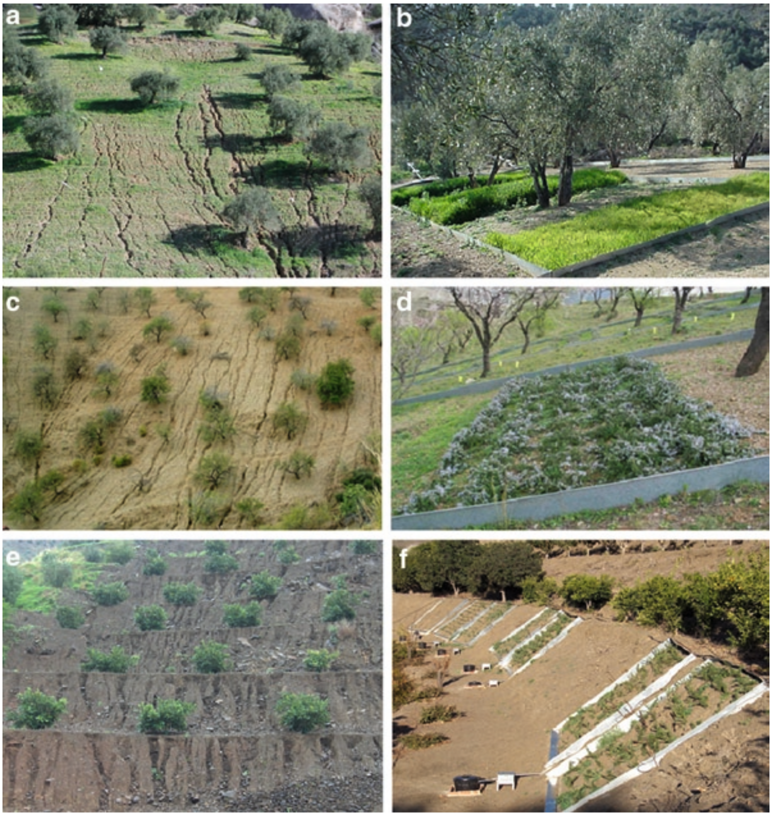

Fig. 5 Gullies in hillslopes with olive (**a**) and almond (**c**) orchards, in terraces with avocado orchards (**e**). Soil erosion prevention by intermittent plant strips in olive (**b**) and almond (**d**) orchards, in the taluses of orchard terraces (**f**)

sustainable use should be compatible with increasing soil organic matter to improve the soil quality for sustaining food productivity and to control soil residual nutrients that aggravate environmental problems. To control soil residual nutrients by increasing organic carbon, it will be necessary to employ fertilization techniques to synchronize with crop growth using post-planting application and soil testing to determine the optimum fertilizer application for the expected soil organic matter and organic material mineralization.

The cultivation of cover crops is a more attractive measure, since cover crops have been shown to prevent N leaching to groundwater by accumulating excess soil N (Wagger and Mengel 1988; Gu et al. 2004). Cover cropping is the only technique for improving the N cycle in cultivated soil that recycles the soil residual N and turns it into nutrients for subsequent crops. In this sense, according to Komatsuzaki and Mu (2005) the rye cover accumulated soil N as the soil residual N level rose. Similar prevention in controlling the N transport in agricultural runoff was found by using plant strips and plant covers on cultivated slopes and in orchard terraces, respectively (Durán et al. 2008; Rodríguez et al. 2005, 2009a). Cover crops have many other benefits as well, such as supplying soil organic matter, adding biological fixed N, suppressing weeds, and breaking pest cycles (Peet 1996; Sarrantonio 1998). They may also be able to enhance soil ecological diversity and perform essential activities to enhance soil health.

Soil organic carbon has the potential to improve soil structure, provide essential plant nutrients, and has an important role in pollution prevention, groundwater protection, and the promotion of biodiversity. However, soil organic carbon is reactive and an increase in organic carbon may also have negative impacts on local environments if the soil is not properly managed. To meet the growing demand for and pressures on soil and water resources, it will be essential to develop and adopt ecofriendly, and sustainable soil-management practices.

On the other hand, Bauhus et al. (2002) reported that changes in soil organic carbon, fail to meet several of the attributes of what is commonly regarded as a good ecological indicator. Of particular concern are the changes in soil organic carbon resulting from charcoal inputs, which are difficult to interpret with regard to soil fertility. Without further qualifications, the changes in soil organic carbon cannot be recommended for implementation as an indicator of sustainable soil management in native eucalypt forests.

Even though soil-management measures for sustainable use may be benefiting the public as a whole, there may be little or no direct benefit to the farmer. Thus, when developing a soil-management strategy for sustainable agro-ecosystems, some political and social approaches will be needed.

The United Nations Framework Convention on Climate Change recognizes that management of the terrestrial biosphere can contribute to mitigation of climate change. Within the context of climate-change policy, emission and removal of greenhouse gases resulting from direct human-induced impacts on the terrestrial biosphere are accounted for within the sector known as land use, land-use change, and forestry. Besides their relevance to the United Nations Framework Convention on Climate Change objectives, measures undertaken in the land use, land-use change, and forestry sector are relevant to several other multilateral environmental agreements that have entered into force during recent years, particularly the United Nations Convention to Combat Desertification (UNCCD-United Nations 1994) and the Convention on Biological Diversity (CBD-United Nations 1993).

In this context, land use, land-use change, and forestry measures implemented to mitigate greenhouse-gas emissions may also affect, positively or negatively, desertification and the conservation of biodiversity (Table 6). Reversing land degradation builds resilience in natural and managed systems, sustaining production and protecting biodiversity. Activities that promote adaptation to climate change can also contribute to the conservation and sustainable use of biodiversity and sustainable land management. Measures that protect or enhance biomass and soil organic matter stocks tend to deliver benefits for all three environmental objectives.

Table 6 Land use, land-use change and forestry measures proposed for climate change: their likely impact on climate change, biodiversity, and desertification by Cowie et al. (2007)

Land use change	Climate change	Biodiversity	Desertification
Conversion from conventional cropping to:			
Reduced tillage	Increase or no change in SOC 0 – +, decreased fossil fuel use +	Increased biodiversity in soil depending on herbicide use +	Reduced erosion +, increased water-holding capacity +
Crop residue retention	Increased SOC + +	Increased soil biodiversity + +	Improved soil fertility +, reduced erosion + +, increased water-holding capacity +
Perennial pasture and permanent crops	Increased SOC + +, increased biomass 0 – + +. Leakage: decreased biomass and SOC on other land converted to arable – – to–	Dependent on pasture/crop species 0 to + +. Leakage: decreased biodiversity on other land converted to arable – – to–	Reduced erosion + +, increased infiltration and water-holding capacity +
Organic amendments such as manure, compost, mulch, biosolids	Increased SOC + to + + +	Possible increase in soil biodiversity, or decrease if amendments are contaminated, e.g. with heavy metals – to + +	Improved soil fertility + + +, reduced erosion +, increased water-holding capacity + +
Improved rotations, e.g. green manure, pasture phase, double cropping (no fallow)	Increased SOC +	Increased biodiversity in soil, above ground +	Improved soil fertility +, increased water-holding capacity +
Fertilisation	Increased biomass + to + +, increased N_2O emissions – – to –, increased GHG costs of chemical fertiliser production –	Possible negative offsite impact on native, especially aquatic, species – – to 0	Increased fertility increases land cover + + +, some fertilisers, e.g. ammonium salts can cause acidification –

Irrigation	Increased biomass +, GHG costs of pumping irrigation water –, increased fertiliser use –, higher N_2O emissions –, salinisation may cause off-site loss of biomass –, off-site carbon gains because less land is needed for food crops and more land can be allocated to renewable energy or afforestation + to + +	Impact dependent on the land use system displaced, but may include loss of native remnants, reduced diversity of crop species – – to 0, salinisation may cause off-site loss of biodiversity – – to –, off-site biodiversity gains because less land is needed for agriculture and more land can be allocated to conservation reserves + to + +	Increased productivity but high risk of soil salinisation – – – to +
Bioenergy crops	Displacement of fossil fuels + + +, impact on biomass dependent on bioenergy crop species: annual crops – to 0, perennial woody crops + to + +, increased biomass removal may reduce SOC – to 0, increased fertilizer requirements to replace additional nutrients removed –	Impact on biodiversity dependent on bioenergy crop species: annual crops 0, perennial woody crops + to + +	Dependent on bioenergy crop species: perennial bioenergy crops may increase land cover, reduce salinity +; increased removal of biomass in annual bioenergy crops may reduce soil protection and increase removal of SOC –
Organic farming	Possibly higher SOC 0 to +. Leakage: lower yield per ha so more area required: decreased biomass on other land converted to arable – – to –	Increased on-site biodiversity (no pesticides) +. Leakage: lower yield per ha so more area required for cropping – – to –	Increased SOM reduces erosion, increases water holding capacity +. Leakage: lower yield per ha so more area cropped – – to –

(continued)

Table 6 (continued)

Land use change	Climate change	Biodiversity	Desertification
Plantation	Increased biomass + + +. Possible leakage: decreased biomass and SOC if other land converted to arable; impact dependent on carbon stock of other land – – to –	Biodiversity increase above ground and belowground + +. Possible leakage: decreased biodiversity off-site if other land converted to arable – – – to –, reduced stream flow – –	Reduced wind and water erosion + + +, reduction in dryland salinity + +
Native forest/woodland	Increased biomass + +, increased SOC + +, decreased fossil fuel use +. Possible leakage: decreased biomass and SOC increased GHG emissions if other land converted to arable; impact dependent on carbon stock of other land – – to –	Biodiversity increase above ground and belowground + + +. Possible leakage –, decreased biodiversity off-site if other land converted to arable – – to –, reduced stream flow –	Reduced wind and water erosion + + +, increased transpiration reduces dryland salinity + +
From conventional grazing to:			
Higher productivity pasture species, e.g. convert annual to perennial species, add legume	Increased biomass +, increased SOC + +, reduced CH_4 from enteric fermentation due to higher quality feed +	May increase plant biodiversity 0 to +, increase in bg biodiversity +	Increased land cover reduces erosion + +
Conservative grazing/cutting method and frequency	Increased biomass and SOC +	Protects species sensitive to over – grazing +	Increased land cover, reduced compaction reduces erosion + +
Fertilisation	Increased biomass and SOC + – + +	Possible negative impact on native grasslands – – to 0	Increased productivity increases land cover + +
Forest	SOC may increase or decrease depending on relative productivity – to +, increased biomass + + +. Leakage: decreased biomass and SOC on forested land converted to grazing – – to –	Impact dependent on the pasture system replaced, and forest type but may include loss of native grasslands – – to +	Increased transpiration reduces dryland salinity + +, reduced wind erosion + to + + +

Bioenergy crops	Displacement of fossil fuels + + +, impact on biomass dependent on bioenergy crop species: annual crops 0 to –, perennial woody crops + to + +, reduced SOC due to increased biomass removal and soil disturbance, especially for annual crops – – to –, increased fertiliser requirements to replace additional nutrients removed –	Impact on biodiversity dependent on pasture system replaced and bioenergy crop species: annual crops –, perennial woody crops + to + +, if native grasslands replaced +	Impact dependent on bioenergy crop species: tillage reduces land cover, increases soil erosion annual crops – – to – perennial woody crops – to 0
Forest management			
Irrigation or fertilisation	Increased biomass +, increased SOC +, increased GHG cost of irrigation/fertiliser	May inhibit native species –	Increased cover and SOC +, potential for salinisation – –
Extend rotation	Increased average carbon stock in biomass and SOC + to + +	Enhanced onsite biodiversity + +	Less frequent soil disturbance +
Protection against deforestation/degradation	Avoids loss of biomass and SOC + + +	Protects biodiversity + + +	Prevents degradation + + +

SOC soil organic carbon, *SOM* Soil organic matter, *GHG* greenhouse gas

Beneficial and detrimental trends are indicated by + and –, respectively. The significance of the impact increases from 0 (no impact), + or – (minor impact) to + + + or – – – (large impact)

5 Land-Use Change

Land-use change is a complex, dynamic process that links together natural and human systems. It has direct impacts on natural resources: soil, water, and the atmosphere (Meyer and Turner 1994) and is thus directly related to many environmental issues of global importance. The large-scale deforestations and subsequent transformations of agricultural land in many areas are examples of land-use change with impact that will likely be strong on biodiversity, soil degradation and the earth's ability to support human needs (Lambin et al. 2003). Land-use change is also one of the important factors in the climate-change cycle and the relationship between the two is interdependent; changes in land use may affect the climate, while climatic change will also influence future land use (Dale 1997; Watson et al. 2000). In addition, Vanacker et al. (2003) reported that land use changes are complex relationships arising out of a wide variety of social objectives, such as the need for food, housing, recreation, or energy. Driving forces of land-use change have been grouped into a number of broad categories, such as economics, drought, earthquake, cropping trends, new technologies, and government policies, to name just a few (Heilig 1996; Reid et al. 2000; Geist and Lambin 2002). According to Shao et al. (2005), these all can be grouped into four factors: biophysical, institutional, technological, and economic, which cannot be understood independently.

Land-use change, as one of the main driving forces of global environmental change, is central to the sustainable development debate. The types of land use are distinguished as land-cover conversion, i.e. the complete replacement of one cover type by another, and land-cover modification, i.e. more subtle changes that affect the character of the land cover without changing its overall classification (Turner et al. 1993; Lambin et al. 2000). Land-use change happens at every spatio-temporal scale. However, the literature on LUC indicates that land-use changes are affecting many aspects of the earth's systems (Velázquez et al. 2003; Lespez 2003; Tomich et al. 2004; Mahe et al. 2005).

The impact of land use, land-use change, and forestry on climate-change mitigation, protection of biodiversity, and desertification is shown in Table 6 according to Cowie et al. (2007), which are a result of the influence of human intervention on the underlying processes that drive greenhouse-gas emissions, integrity of natural ecosystems, and land degradation, respectively. Although some land use, land-use change, and forestry measures can be detrimental to conservation of biodiversity or mitigation of land degradation, there are many opportunities for synergistic interactions. For example, many dryland ecosystems are sites of significant biodiversity; conservation and restoration of this habitat, while protecting these ecosystems, also increases C stocks, and reduces land degradation (Cowie et al. 2007).

Table 7 shows the soil erosion and runoff rates under different land uses at the watershed "El Salado" (SE, Spain). Vegetation under different land uses can reduce erosion by developing a canopy to intercept raindrops. In doing so, the raindrop loses the energy to erode the soil. Also, the litterfall increase soil organic matter and roughness of the ground while roots of the vegetation knit the soil together, reducing

Table 7 Average soil erosion and runoff for different land-use types at the Salado watershed

LUT	Plant cover/Management technique	Slope (%)	Soil erosion (Mg ha^{-1} $year^{-1}$)	Runoff (mm $year^{-1}$)
Forest	*Pinus sylvestris*	36	0.02	0.1
	Pinus nigra	33	0.01	0.1
	Pinus pinaster	22	0.01	0.2
	Pinus halepensis/Pinus pinea	45	0.03	0.2
Farmland	Olive/conventional tillage	30	5.7	11
	Olive/No-tille with barley strips	30	2.1	19.8
	Almond/Bare soil with herbicide	35	12.3	58
	Almond/No-till with thyme strips	35	0.4	5
	Almond/No-till with barley strips	35	1.7	23.8
	Almond/No-till with lentil strips	35	5.2	47.8
	Rainfed wheat	36	3.8	56.5
Shrubland	*Ulex parviflorus*	22	0.01	0.1
	Lavandula stoechas L.	13	2.6	102
	Lavandula lanata L.	15	2.0	51
	Origanum bastetatum L.	15	1.6	36
	Genista umbellata Poiret	13	1.5	50
	Thymus baeticus Boiss.	13	1.4	56
	Santolina rosmarinifolia L.	13	0.7	44
	Salvia lavandulifolia Vahl.	13	0.5	33
	Thymus serpylloides Bory	13	0.2	17
	Rosmarinus officinalis L.	36	0.05	3.2
Grassland/degraded land	Nativespontaneous vegetation	36	0.08	2.1
	Bare soil	13	7.8	154

the runoff velocity and increasing infiltration. Therefore, the current erosion rates are affected by human activity, in particular the clearing of natural vegetation for agricultural purposes, and are believed to be significantly higher than those found under native vegetation.

Since Roman times, the sloping and mountainous land in southern Europe has been used for olive orchards, which continue provide a major source of income and employment for local populations. The production systems were economically and environmentally sustainable, but recent developments have so badly affected them, that they are now unproductive and environmentally disastrous. In this context, the main objective of the OLIVERO project (www.olivero.info) was to analyse the future of these olive-production systems on sloping and mountainous land in the European Mediterranean basin (Stroosnijder et al. 2008). According to the OLIVERO project this concerns the following social, economic, and environmental developments: (1) migration of rural population to coastal and urban areas; (2) European Union support to the olive sector in the form of production subsidies encouraging flat-land farms more than hillside farms with no incentives for more sustainable land and water use; (3) increasing production in and competition from countries outside

Europe, where olive area in the last decade expanded by 9% compared to 3% in the European Union; (4) intensification of olive cultivation on flat land to withstand this competition (while originally one of the best land-use options on hilly rainfed land, olive production has now migrated to flat irrigated land, thereby replacing horticultural crops; (5) losing in production competition with flat land, the sloping and mountainous olive plantation systems are no longer well managed and cause environmental havoc (annual soil erosion losses of 80 t ha^{-1} are unlikely and flood risks are now extremely high); (6) abandonment of sloping and mountainous olive plantation systems has sharply increased fire incidence in southern Europe.

The future of these sloping and mountainous olive plantation systems is likely to follow one of the three paths of land use: (1) some will be gradually abandoned or transformed into nature conservation areas; (2) some will follow in the olive production intensification patterns typical in the valleys (now possible with drip irrigation); and (3) others will continue to be managed in a more extensive way, maybe supplementing olive production income with other activities, e.g. off-farm employment and tourism.

In all three cases attention needs to be paid to sustainable land husbandry and in particular to improving and conserving the soil and water resources (Xiloyannis et al. 2008; Metzidakis et al. 2008). While there are new sustainable technologies for hilly land and the European Union has now begun considering the environmental issues, there is a clear need to come up with the right technological packages and policy incentives for the different areas concerned (De Graaff et al. 2008; Goméz et al. 2008). Thus, most programmes involved in monitoring and assessing environmental conditions are ultimately associated with issues of sustainability.

The quality of water, soil and air resources, ecosystem processes and functions, as well as the climate system itself through greenhouse-gas fluxes and surface albedo effects have all undergone profound changes in the past century (Turner 1989; Burel et al. 1993; Fu et al. 1994; Olsson et al. 1997; Leitch and Harbor 1999). These changes are likely to be even more momentous in this century. Determining the effects of land-use change on the earth's system depends on an understanding of past land-use practices, current land use patterns, and projections of future land use, as affected by human institutions, population size and distribution, economic development, technology, and other factors. Therefore, land use is receiving increased attention in life-cycle assessments (Pennington et al. 2004; Brentrup et al. 2004; Tan 2005; Wagendorp et al. 2006). Whereas, a few years ago, most land-use change research had been focused on why – i.e. why land-use change takes place – including explanations and driving forces of land-use change, the focus is now mostly on what – i.e. what is being affected by land-use change.

Modern environmental change is dominated by human influences, which are now powerful enough to exceed the bounds of natural variability. The main source of global environmental change is human-induced changes in land use. Therefore, land use is often a driver of environmental and climatic change, and a changing environment in turn affects land use practices (Shaw et al. 2002; Levy et al. 2004; Baker 2005). Although there has been progress in monitoring and understanding environmental change (Zavaleta and Hulvey 2004; Van Beek and Van Asch 2004), it is still impossible to explain the underlying processes and mechanisms of ecological impact of land-use change. Additionally, it is clear that these changes will be increasingly manifested in important and tangible ways, such as loss of biodiversity, diminished land productivity, land degradation, water contamination, and receding groundwater tables.

Currently, the most fundamental obstacle to progress in understanding and predicting human impact on environmental changes lies in the lack of a comprehensive and integrative theory of human-land relationships. According to Tenge et al. (2004) and Olgerts et al. (2005) the recent growth of research into land use change has revealed the inadequacy of current theories. The theoretical explanation of land-use change seeks ultimately to understand the underlying forces driving changes.

5.1 Soil Organic Carbon Loss and Land Management to Restore Organic Carbon

Many long-term experiments on land-use change demonstrated significant changes in soil organic carbon (Smith et al. 1997, 2000, 2001, 2002). A recent modelling study examining the potential impact of climate and land-use change on soil organic carbon stocks in Europe confirmed that land-use change has a larger net effect on soil organic carbon storage than projected climate change (Smith et al. 2005).

In line with Guo and Gifford (2002), meta-analysis of long-term experiments, showed that converting forest land or grassland to croplands caused significant loss of soil organic carbon, whereas conversion of forest to grassland did not result is organic carbon loss.

The largest per-area losses of soil organic carbon occur where the C stock are largest, for example in highly organic soils such as peat lands, either through drainage, cultivation, or liming. Organic soils hold enormous quantities of soil organic carbon, accounting for 329–525 Pg C, or 15–35% of the total terrestrial C (Maltby and Immirzi (1993), with about one fifth (70 Pg) located in the tropics.

In this sense, according to Nykänen et al. (1995), Lohila et al. (2004) and Maljanen et al. (2001; 2004), the cultivated peat fields in Europe can lose significant amounts of soil organic carbon through oxidation and subsidence from 0.8 to 8.3 t C ha^{-1} $year^{-1}$. Consequently, the potential soil organic carbon loss from land-use change on highly organic soils is very large. In short, soil organic carbon tends to be lost when converting grasslands, forest or other native ecosystems to croplands, or by draining, cultivating or liming highly organic soils. Soil organic carbon tends to increase when restoring grasslands, forests or native vegetation on former croplands, or by restoring organic soils to their native condition. Where the land is managed, the best management practices that boost C inputs to the soil or reduce losses help to maintain or raise soil organic carbon levels Smith (2004) (Table 8).

The rate of C input into the soil is related to the productivity of the vegetation growing on that soil, measured by Net Primary Production, which varies with climate, land cover, species composition and soil type. Moreover, the Net Primary

Table 8 Activities and practices for soil carbon sequestration

Activity	Practice/specific management change
Cropland management	Agricultural/increased productivity Agricultural/rotations Agricultural/catch crops Agricultural/less fallow Agricultural/more legumes Agricultural/de-intensification Agricultural/improvement of cultivars Nutrient management/fertilizer placement Nutrient management/fertilizer timing Tillage/reduced tillage Tillage/no-tillage Residue management/reduced residue removal Residue management/reduced residue burning Upland water management/irrigation Upland water management/drainage Set-aside and land-use management/set aside Set-aside and land-use management/wetlands Agroforestry/tree crops, shelterbelts, etc.
Grazing-land management	Livestock grazing intensity Fertilization Fire management Species introduction More legumes Increased productivity
Organic soils	Restoration/rewetting/abandonment
Degraded lands	Restoration

Production shows seasonal variation due to its dependence on light and temperature. For example the broadleaf temperate forests are highly productive for part of the year only (Malhi et al. 2002). According to Jones and Donnelly (2004), over longer time periods, a proportion of Net Primary Production enters the soil as organic matter either via plant leachates, root exudates, or by decomposition of litter and fragmented plant structures, where it is converted back to CO_2 and CH_4 via soil-heterotrophic respiration processes.

In this context, soil C sequestration can be achieved by increasing the net flux of C from the atmosphere to the terrestrial biosphere by increasing global C inputs to the soil via increasing the Net Primary Production, by storing a larger proportion of the C from Net Primary Production in the longer-term C pools in the soil, or by reducing C losses from the soils by slowing decomposition. According to Smith et al. (2005) for soil C sinks, the best options are to increase C stocks in soils that have been depleted in C, i.e. agricultural soils and degraded soils, or to halt the loss of C from cultivated peat lands. From the studies in European cropland (Smith et al. 2000), US cropland (Lal et al. 1998), global degraded lands (Lal 2001) and global estimates (Cole et al. 1996; IPCC 2000), a global soil C-sequestration potential of 0.9 ± 0.3 Pg C year^{-1} was estimated by Lal (2004a, b), between a 1/3 and 1/4 of the annual increase in atmospheric C levels. Moreover, Lal (2004a) estimated that over 50 years, the level of C sequestration would restore a large part of the C lost from soils historically.

The most recent report by Smith et al. (2007) estimated that the technical potential for soil organic carbon sequestration globally is about 1.3 Pg C year^{-1}, but this is very unlikely to be met.

Most of the estimates for the sequestration potential of activities in agricultural soils, listed in Table 9, range from about 0.3–0.8 t C ha^{-1} year^{-1}, but some estimates are outside this range (IPCC 2000; Lal 2004a; Smith et al. 2000; Follett et al. 2000; Nabuurs et al. 1999; Smith et al. 2007). In addition, when considering soil C-sequestration options, it is important also to consider other side effects, including the emission of other greenhouse gases. Smith et al. (2007) showed that soil C sequestration accounts for about 90% of the total global mitigation potential available in agriculture by 2030.

Soil-C sinks are not permanent and will continue only for as long as appropriate management practices are maintained. If a land-management or land-use change is reversed, the C accumulated will be lost, usually more rapidly than it was accumulated (Smith et al.1996). Also, soil C sinks increase most rapidly soon after a C–increasing land-management change has been implemented, but soil-C levels may decrease initially if there is significant disturbance, e.g. when land is afforested. Sink strength (i.e. the rate at which C is removed from the atmosphere) in soil becomes weaker with time, as the soil-C stock approaches a new equilibrium. At equilibrium, the sink has saturated: the C stock may have increased, but the sink strength has decreased to zero (Smith 2004). According to IPCC (2000) this process is termed “sink saturation,” that highly variable phenomenon. The period for soils in a temperate location to reach a new equilibrium after a land-use change is about 100 years (Jenkinson 1988) but tropical soils may reach equilibrium more quickly. Soils in boreal regions may take centuries to approach a new equilibrium.

Land management can profoundly affect soil-C stocks and careful management can be used to sequester soil C. As with all human activities, the social dimension needs to be considered when implementing soil C-sequestration practices.

In addition, it is crucial to understand the processes that determine soil-C losses and the fate of the C once lost from the soil in order to provide sustainable solutions for mitigating these C losses as part of sustainable land use and balancing of carbon budgets. Table 9 shows an indication of the estimated gains or losses of soil C for a range of land-use changes, as detailed by Freibauer et al. (2004) and Soussana et al. (2004). The degree of uncertainty in this data is either due to lack of relevant studies, e.g. forest to grassland pasture, or to variations caused by contrasting management regimes on the same land-use type, particularly arable and grasslands (Soussana et al. 2004).

Consequently, modern sustainable land use has to augment soil-C sequestration, applying available management practices that could be implemented to

Table 9 Potential changes in soil carbon storage in terms of conversion of land-uses

Land-use change	Net C rate (*uncertainty*) (× 10^3 kg C ha^{-1} $year^{-1}$)	Source
Arable to ley/arable rotation	1.6	Smith et al. (1997)
Arable to grassland (50 year)	0.3–0.8	IPCC (2000)
Arable to grassland (35 year)	0.63	Jenkinson et al. (1987)
Arable to grassland (15–25 year)	0.3–1.9 ± 0.6, (*100%*)	Vleeshouwers and Verhagen (2002); Guo and Gifford (2002); Murty et al. (2002)
Arable to grassland short leys (20 year)	0.35	Soussana et al. (2004)
Arable to permanent pasture	0.27	Post and Kwon (2000)
Arable to forestry (115 year)	0.52 + 1.53 (C in veg.)	Hooker and Compton (2003)
Arable to forestry	0.62 + 2.8 (C in veg.)	Smith et al. (2000); Falloon et al. (2004)
Arable to forestry (25 year)	0.3–0.6, > *50%*	Guo and Gifford (2002); Murty et al. (2002)
Arable to forestry	0.5–1.4, > *50%*	Maljanen et al. (2001)
Permanent crops to arable	−0.6 and 1.0–1.7, *>50%*	Smith et al. (1996); Guo and Gifford (2002); Murty et al. (2002)
Grassland-arable (20 year)	−0.95 ± 0.3, *95% CI*	Soussana et al. (2004)
Grassland-arable	−1.0 to −1.7, *>50%*	Smith et al. (1996); Guo and Gifford (2002); Murty et al. (2002)
Grassland-afforestation (90 year)	0.1 ± 0.02, *95% CI*	Soussana et al. (2004)
Moorland-grassland	−0.9 to −1.1	Soussana et al. (2004)
Forestry-arable	−0.6	Guo and Gifford (2002); Murty et al. (2002)
Forestry-grassland	−0.1 ± 0.1, *95% CI*	Soussana et al. (2004)
Native vegetation-grassland	0.35	Conant et al. (2001)
Peat land-cultivation	−2.2 to −5.4	Freibauer et al. (2004)
Wetland-arable (temperate and boreal)	−1.0 to 19	Watson et al. (2000)
Wetland restoration	0.1–1.0	Watson et al. (2000)
Revegetation on abandoned arable	0.3–0.6, *>50%*	Poulton (1996)
Revegetation on wetlands from arable	2.2–4.6, *>50%*	Kamp et al. (2001)
Revegetation on wetlands from grassland	0.8–3.9, *>50%*	Kamp et al. (2001)
Conservation	>2.2, *>50%*	Freibauer et al. (2004)

+ indicates soil C gains; – indicates soil C losses protect and enhance existing C sinks now as well as in the future. In this context, Smith and Powlson (2003) developed arguments for soil sustainability but the policy options are equally applicable to soil C sequestration. Since such practices are consistent with, and may even be encouraged by, many current international agreements and conventions, their rapid adoption should be encouraged as widely as possible.

Table 10 shows a number of small- and large-scale measures that may be considered when following the "best-practice guidelines" under varied land-uses prevalent in the United Kingdom (Post and Kwon 2000; Carling et al. 2001; Conant et al. 2001; Farmer and Nisbet 2004; Forestry Commission Scotland 2006; Freibauer et al. 2004; Jones and Donnelly 2004; Lal 2004b, c; Smith 2004; Soussana et al. 2004; Stott and Mount 2004).

5.2 Effects of Land-Use Change on Soil and Water

Land use is one of the main factors, as it influences the distribution of elements, particularly processes and affects morphological, chemical, and physical soil conditions (Leifeld and Kogel 2005; Mando et al. 2005).

Soil physical parameters like aggregates, particle-size distribution, bulk density, etc., are key factors in the functioning of soil with their abilities to support plant and animal life, and to moderate environmental quality with particular emphasis on soil-carbon sequestration and water quality. Although they often depend on the parent material, that is, their development and aggregation occur within the context of natural pedogenic processes and activities (Pulleman and Marinissen 2004; Montero 2005), many land-management practices are known to influence soil physical properties by altering the microsite of the soil and near-ground temperature and moisture regimes as well as wet-dry and freeze-thaw cycles. These include cultivation, crop type, and the application of organic wastes. The effects of cropping systems on soil physical properties are often related to the increase in SOM related the action of growing plant roots with both aggregate formation and breakdown. Cultivation generally tends to break down aggregates. The stability of soil aggregates often diminishes for the growth of annual crops, such as wheat or corn. Residue quantity had a larger effect on splash detachment, shear strength, and aggregate stability than that of residue type. Long-term pastures are ideal for improving soil aggregation as well. Additionally, changes in temperature and moisture levels resulting from land use affect microbial and biotic activities, which in turn alter decomposition rates (Sveistrup et al. 2005).

Table 10 Land management options that could increase soil C pools[a]

Croplands	Convert marginal cropland to native vegetation, grasslands or forestry; improve crop production and erosion control; improve management of set-aside and field margins; improve farming on eroded soils, erosion control buffer strips, riparian filters; reduced or no-tillage; improved waste management; eliminate bare fallow; organic amendments, increased efficiency of animal manure, sewage sludge and composting; inter-sowing and increased duration of grass leys; improve crop rotations; use perennial crops; use deeper rooting crops; use bioenergy crops; improve water and nutrient (fertilizer) management; increase number of agroforestry systems; do not use highly organic soils for cropping.
Grasslands	Convert cultivated lands to well-managed permanent grasslands, species selection; decrease erosion and degradation; eliminate disturbance, e.g. fire protection in established pastures; increase forage production by improved fertilization, irrigation, inter-sowing of grasses and legumes; improve grazing and livestock management with controlled light-to-moderate stocking density; moderately intensify nutrient-poor permanent grasslands; introduce earthworms, improve soil structure; maintain a diverse plant community with a dense rooting system.
Forestry	Forest and Water Guidelines by the Forestry Commission, "best practice" guidelines; increase forest stock; continuous-cover forestry to encourage natural regeneration; conserve soil and water resources; improvement of site preparation and planting techniques to decrease erosion; streamside management with uncultivated buffer zones to stabilize soil and reduce acidification; design of forest roads and network of drains, culverts and sediment catch pits; reduction of disturbances from wind and fire; minimisation of soil and water impacts and reduction of clear-felling operations to phased felling; minimisation of nitrate leaching, enhancement of base cation retention by early revegetation; use of species with high NPP or increase of the number of actively sequestering younger forests; application of nutrients and micronutrients as fertilizers or biosolids; aesthetic planting of previously native trees and shrubs, increase of biodiversity; maintenance of open bog and moorland habitats; extension of guidelines to include conservation, landscape, and recreation; planting of trees on mineral soils in preference to highly organic soils.
Peat lands and wetlands	Wetland protection, restoration and revegetation on bare peats; prevention of wind and water erosion; reduction of peat extraction and disturbance; preserve biodiversity; rehabilitate acidified surface waters; afforestation only in appropriate areas; controlled burning; aesthetic planting of previously native trees and shrubs; where possible block drains and restoration of the water table.

NPP Net Primary Production; [a] Dawson and Smith (2007)

Essential indicators of soil quality, e.g., soil fertility, soil moisture, soil pollution, etc., play an important role in affecting soil chemical, physical, and biological properties. Accumulating evidence suggests that changes in land use significantly influence the main soil-quality parameters (Eswaran and Kimble 2003; Riley et al. 2005). Conversion from forest to agricultural land strongly impacts soil nutrients and microbial biomass, e.g., soil organic matter, total nitrogen, water-holding capacity, and pH (Sharma et al. 2004; Agustin et al. 2004). Land-use structure types of slope farmland-grassland-forest and terrace-grassland-forest have a better capacity to maintain soil nutrients (Zalidis et al. 2002; Fu et al. 2003; Gregor and Anette 2002).

Soil moisture is a critical environmental variable, as it plays a key part in land surface and atmospheric interactions. It alters energy balances near the soil surface and the rate of water cycling between land and atmosphere. For example, it significantly affects infiltration, evapotranspiration, and surface as well as subsurface runoff processes (Ronda et al. 2002). However, most cases demonstrate that land use, a human disturbance to land-surface characteristics, including the construction of dams, and intensification and expansion of agricultural practices, are considered as explanatory factors for the observed soil-moisture behaviour (Mahmood and Hubbard 2003, 2004; Wilson et al. 2005). Extremely dry or wet conditions enhance and reduce, respectively, the forcing of land use on soil-moisture variability at an annual time scale. Thus, large-scale interannual climate variations and land use jointly affect soil-moisture variability at this scale.

Land-use practices are assumed to have a major impact on both the quality and the cycle of water resources (Hundecha and Bárdossy 2004; Dawes et al. 2004). Hydrological effects of land use are unveiled in several ways both directly and indirectly. For instance, these water-balance responses follow land use change results in land and river salinisation, changes flood frequency and flow regime, and augments surface waterlogging, with all the ecological and economic consequences (Sullivan et al. 2004; Jewitt and Garratt 2004; Dawes et al. 2004). Intensive cultivation and livestock husbandry will have negative hydrological effects through the application of fertilizers, pesticides, herbicides, and land drainage. Water quality is likely to be degraded by agricultural intensification through NO_3 and PO_4 concentrations because of heavy concentrations of inorganic fertilizers (Clarke et al. 2002). Pesticides will also cause health risks to humans and wildlife when washed by rainfall into water bodies and underground water, bringing about possible water toxicity (Ares 2004; Berenzen et al. 2005). Farm wastes such as manure and slurries from farm livestock and pesticide containers are all potential sources of both surface and groundwater pollution (Smith et al. 2004; Grey et al. 2005).

The impact of land-use change on the hydrologic cycle involves primarily evaporation, runoff, and erosion. The total evaporation from a given land use is influenced by aerodynamic resistance to transportation of vapour between the evaporating surface and the atmosphere. The balance between the atmospheric and radiation demand leads to the occurrence of water at the evaporating surface (Sullivan et al. 2004). Depending on the rate of extraction, the extent of the free-water surface in lakes and swamps can be reduced. Also altered may be the availability of soil water to plants in the case of the deep-rooted plants that will replace shallow-rooted grasses, provoking declines in the water availability during the dry season These changes in the availability of water at the evaporating surface alter the evaporation rate, leading to changes in the near-surface atmospheric conditions; this, depending on the extent of the land use, can lead to a basin-scale climatic change (Schneider et al. 2004; Hope et al. 2004). At the same time, replacing grasses with taller vegetation will increase the aerodynamic roughness and lower aerodynamic transport resistance. Agricultural operations normally involve soil-structure disruptions, upsetting the balance between percolation and runoff. These activities affect the timing of runoff and determine the velocity at which net rainfall reaches water bodies. Infiltration rates will be augmented as a result of greater porosity during tillage and reduced considerably towards harvesting due to soil compaction by raindrops (Rhoton et al. 2003; Lado et al. 2004; Gómez et al. 2001). The planting of trees can affect seasonal flows through increased interception of water and greater transpiration. However, removal of the vegetation cover and exposure of the soil surface increases the susceptibility of the soil to erosion through the detachment of soil particles, compaction, and sealing of soil surface (Gemma et al. 2003; Huisman et al. 2004; Bartholy and Pongracz 2005).

5.3 Impact of Land-Use Change on Biodiversity

At present, loss of biodiversity, inducing high rates of extinction and a worldwide depletion of biological diversity at the genetic, species and ecosystem levels, can be linked to the destruction of natural habitats as a result of land-use change at different scales (farmland expansion, deforestation, urbanization, etc.), and is presently considered one of the most urgent environmental problems (Chemini and Rizzoli 2003; Medley 2004; Zebisch et al. 2004). The ecological consequences of biodiversity loss have aroused considerable interest and controversy during the past decade. Major advances have been made in describing the relationship between species diversity and ecosystem processes, in identifying functionally important species and in revealing underlying mechanisms (Loreau et al. 2001; Brown et al. 2001; Wardle et al. 2003).

Undoubtedly, underlying processes and mechanisms that result in biodiversity loss remain poorly understood. Our limited knowledge has come mainly from studies of terrestrial habitats that have been transformed by human activities. The single most important fact concerning biological diversity is that it is not evenly distributed over the planet (Jeanneret et al. 2003; Solé et al. 2004).

Conversion, degradation, and fragmentation threaten the integrity of ecosystems worldwide. Today, biological species live in steadily more fragmented ("island") habitats isolated from each other within a matrix of human constructions. Land use and habitat conversion are, in essence, a zero-sum game: land converted into farmland to meet the global food demand comes from forests, grasslands, and other natural habitats (Tilman et al. 2001; Jenkins 2003; Hietala et al. 2004). This process is known as forest or habitat fragmentation. This fragmentation, including both the shrinking of the habitat area as well as the its spatial reshaping, has been generally recognized as the primary destroyer of biodiversity and ecosystem function. The consequences of fragmentation for species viability vary from species to species, in some cases depleting genetic variation, in others imposing dispersal barriers and thwarting key biotic interactions (Hale et al. 2001; Van Rossum et al. 2004; Rissler et al. 2004). Barriers, such as intervening patches of unfavourable habitats, roads or dams on waterways, may prevent recolonization from populations in other habitat patches. Habitat corridors (i.e. linear features which connect blocks of habitat) have generally been shown to benefit the movement of animals, palliating the damage caused by fragmentation. For example, the expansion of shrubs and forests have depressed several grassland species, such as rock partridge; some arthropod communities of grassland have also been affected, while many forest species should find new opportunities (Jeanneret et al. 2003; Rustigian et al. 2003; Hudgens and Haddad 2003). However, the majority of species are likely to experience negative impacts from habitat disturbance, especially as patch sizes decline below a minimum required for population viability. Fragmentation can also make species more vulnerable to disease and storms, and perturb relationships between predators and prey (Holland et al. 2003). Additionally, although tropical rain forests harbour over half of all species diversity, the many other ecosystems that contain the remaining 50% also deserve consideration (Bruner et al. 2001; Achard et al. 2002). These include tropical dry forests, tundra, temperate grasslands, polar seas, and mangroves, which all contain unique expressions of biodiversity with characteristic species, biological communities, and distinctive ecological and evolutionary phenomena.

Schmitzberger et al. (2005) investigated the relationship between biodiversity and farming activities in selected Austrian agricultural landscapes, confirming the negative effect of intensive (especially agricultural) land use on biodiversity. A close link between interests of farmers, land-use intensity, and biodiversity can be established (Reidsma et al. 2006; Giupponi et al. 2006). High-production farms supported the lowest nature values on their land, whereas both traditional and innovative farm businesses maintained higher biodiversity within their landscape.

5.4 Land-Use Change and Driving Forces

Most simply, the interactions between humans and the environment are represented by the flow of ecosystem goods and services, the utilization of which usually has environmental repercussions for ecological systems (Bicík et al. 2001; Serra et al. 2008). In terms of the DPSIR (Driving Forces, Pressures, State, Impact, and Response) approach of the European Environment Agency (EEA 1999); human needs “drive” the use of ecosystem structures and processes. The utilization causes “pressures” on the “state” of the ecological systems. These pressures result in: (a) further changes of the systems and (b) alterations of the ecosystems’ capacity to supply ecosystem services. This last step feeds back into the human sphere. Humans rely on ecosystem goods and services and thus evaluate their sustainable provision.

The societal response to changes in the state of the environment differs to a large extent with the degree that the human actors consider essential ecosystem services at risk.

Land-use changes are modelled based on (proximate) driving factors and the resulting changes in land-use patterns are used to calculate a set of indicators that reflect the effects on selected environmental or socio-economic variables (impacts) (Reidsma et al. 2006; White and Engelen 2000). The impact of land-use change may affect future land-use changes as a consequence of such feedback. According to Bossel (1999), such feedback blurs the distinction between impacts and drivers. Examples include soil degradation that affects future land use when soil suitability is a driving factor of land-use change as well. Large-scale deforestation may alter climate conditions and, hence, influence vegetation patterns and the occurrence of forest fires. These may affect land requirements and reclamation potential (Foley et al. 2003). Such feedback can also act through the socio-economic system: intensified land-use practices can generate higher income which, in turn, can trigger investments in further intensification or expansion of the farmed area. It is important to distinguish between positive (amplifying) and negative (attenuating) feedback. Positive feedback is self-reinforcing and concerns interactions between the effects and drivers of land-use change that extend the reach of these changes (Lambin et al. 2003). Unsustainable soil use after deforestation may lead to a higher rate of future deforestation as a consequence of soil degradation.

Negative feedback refers to effects of land-use change that attenuate further change: the response of environmental degradation following deforestation may lead to innovative and more sustainable land conversions, slowing down the rate of forest conversion. Some types of feedback can result in a gradual modification of the land-use system, while others can suddenly provoke the transformation or collapse of the system when it reaches a point of no return. An example is a total ban on logging of mountain forests after a disastrous flood event.

When feedback mechanisms lead to a timely attenuation of the change or associated impact (negative feedback) the system itself shows a certain degree of resilience to the change. In the case of a positive feedback, leading to unsustainable land-use practices and negative impact on key indicators, intervention from policy may be needed to fine tune the feedback process (Lambin et al. 2003).

Feedback mechanisms between land-use change impact and driving factors operate over different temporal and spatial scales. Whereas some types of feedback operate locally, e.g. nutrient depletion of the soil, many feedback mechanisms operate over larger scales such as the landscape scale: as a consequence of off-site effects of erosion/sedimentation processes, through market mechanisms, or even through the global climate system (Foley et al. 2003). Differences in temporal scale result from a delay in response.

The most common feedback mechanism in dynamic modelling approaches is the dependence of land-use change at time t on land use at time $t-1$. Such dependence on current and historic land use is essential to represent the land-use pattern, since conversion possibilities and costs greatly differ according to the type of land use. This kind of feedback leads to being path-dependent in land-use simulations

(Manson 2001; Verburg et al. 2004). Less common in land-use modelling is the simulation of feedback between impact on socio-economic and environmental conditions and the driving factors of land-use change. However, such feedback is essential for a more complete understanding of the dynamics of the land-use system and possible pathways that lead to amplification or attenuation of the changes.

For example, to illustrate the potential of including feedback between types of impact and drivers of land-use change an example is given for a region in southern Spain (Verburg 2006). This case study considers feedbacks between land-use decisions and landscape processes (erosion and sedimentation). The modelling approach accounts for land-use conversions that change the processes of erosion and sedimentation as a result of alterations in water infiltration, management (tillage erosion), and vegetation cover. Thus, erosion and sedimentation processes, in turn, sway land-use decisions.

According to Verburg (2006) this feedback mechanism involves different processes:

1. Erosion and sedimentation processes change the soil depth and consequently determine the suitability for agricultural purposes. Soils in the area are mostly shallow and soil depth is decisive in agricultural land-use choices.
2. If soil depth becomes too shallow for agricultural purposes the land will be abandoned. Swift changes in soil depth are occurring especially in areas where gullies are cut by runoff and highly erosive conditions.
3. Erosion and sedimentation features can often be distinguished by the appearance of gullies or rills, and down-slope fields may be covered by sediments. Depending on the perception of these features by farmers, land-use decisions are affected by lowering the perceived suitability of the location.

The conflicts between biodiversity conservation and human activities are becoming increasingly apparent in all European landscapes. The intensification of agricultural and forestry practices, land abandonment, and other land uses such as recreation and hunting are all potential threats to biodiversity that can lead to conflicts between stakeholder livelihoods and biodiversity conservation. To address the global decline in biodiversity, there is, therefore, a need to identify the drivers responsible for conflicts between human activities and the conservation of European biodiversity and to promote the reconciliation of conflicting interests. Human activities can, in many ecosystems, be beneficial to biodiversity. In grasslands and agricultural landscapes for example, low-intensity management can promote high densities of species (Bignal and McCracken 1996, 2000; Farina 1997; Blanco et al. 1998; Robinson et al. 2001). In Europe, the trajectory and maintenance of the biodiversity of many ecosystems depends directly on traditional types of land use (Dömpke and Succow 1998). However, there is increasing evidence of a global decline in biodiversity (Pimm and Raven 2000; Myers and Knoll 2001; Brooks et al. 2002; Singh 2002). Although many factors are responsible for this decline, the root cause is invariably some form of human activity, mainly associated with changes in land use. To address the global decline in biodiversity there is, therefore, a need to identify the drivers leading to conflicts between human activities and the conservation of biodiversity, and to promote the management of these conflicts.

On the other hand, Antrop (1997) pointed out that for densely populated areas where landscapes change rapidly, and not always according to planning rules, the concept of traditional landscapes offer two approaches which can be use for improving landscape management, landscape architecture and planning. Firstly a general framework of spatial landscape units reflects differences in historical development, which are linked to the local natural conditions. This can be compared to the current situation, and remnants of the old landscapes can be detected and mapped. Secondly, the idealised model descriptions may be used as holistic tools to evaluate the landscapes values and to define ensembles. Thus, ensembles form landscape holons may be used as anchor places to start landscape restoration in a wider area.

5.4.1 Agricultural- and Forest-Policy Drivers

Agriculture including arable land and permanent grassland is one of the most important forms of land use, covering about 43% (137 million ha) of the European Union, with 12 million or more people depending directly on agriculture (Potter 1997). The European Union's Common Agricultural Policy, set up in 1962 to deal with food shortages following the Second World War, is now the main policy driver behind conflicts between agricultural practices and biodiversity. The Common Agricultural Policy initially aimed to boost productivity and provide more food at a lower cost for European Union countries, while also achieving a fair standard of living for farmers. This was achieved through stabilisation of markets (through a single market with common prices) and a more autonomous approach with less reliance on imports and preference given to member states as well as free movement of goods. Habitat degradation or loss, food overproduction, social discontent leading to rural depopulation (Comins et al. 1993; Grove and Rackham 2001) and the cost associated with the accession of another ten countries to the EU in 2004 all led to pressure for the reform of the Common Agricultural Policy (Bignal 1999).

Starting in the mid-1980s, pressure has been building to divert money away from direct subsidies for production and into environmental protection and rural development, and this trend is likely to continue for the foreseeable future. Despite great variations between European Union member states, agri-environment schemes now cover a total of 20% (27 million ha) of the agricultural land in the European Union (EC 1998) but receive only about 4% (1.7 billion €) of the European Agricultural Guidance and Guarantee Fund (Donald et al. 2002).

Conflicts with the protection of forest biodiversity in Europe are due primarily to changing demands concerning forests and forestry. Major conflicts can be linked to overall changes in forest management, such as changes in ownership patterns, transportation systems or even changes in planning strategies. Forestry systems have also changed significantly with intensive harvesting methods, the shortening of crop-rotation times, plantation forestry (often using exotic species) and the increased use of biocides. As with agriculture, technological advances have also been instrumental in enabling a wider use of machinery for timber harvesting, and infrastructure development such as roads for easier transportation of timber. This intensification of forestry practices and the increasingly multi-purpose role of forests have all contributed to a number of initiatives to better understand the status of forests in Europe, their threats, and priorities in conservation.

Examples include the work programme on Forest Biological Diversity at the sixth Conference of the Parties in The Hague in 2002 and the work undertaken by the Ministerial Conference on the Protection of Forests in Europe (MCPFE). Although the Treaties of the European Union make no provision for a comprehensive common forestry policy, the management, conservation, and sustainable development of forests are nevertheless vital concerns of existing common policies such as the Common Agricultural Policy and rural development, environment, trade, internal market, research, industry, development cooperation, and energy policies. Forests are also a component of specific environmental issues such as the European Union Biodiversity Strategy, Natura 2000, and the implementation of the Climate Change Convention.

6 Towards Sustainable Soil Use by Agriculture

Soil degradation and irreversible destruction of agricultural soils are advancing at an alarming rate, threatening the food security of an expanding world population. The decomposition of soil organic matter favours climatic change and loss of an important CO_2-sink. The state of knowledge-report describes the extent of agricultural-soil degradation, its biophysical and socio-economic causes and economic impacts. In previous sections the causes behind the failure and success of soil conservation projects are analysed. It is evident that the failures are not simply because land users lack efficient technology to protect the soil better; the major causes are insufficient participation in technological development and the lack of favourable socio-economic, institutional, and legal conditions. For implementing sustainable agricultural soil use on broader scale to it is essential create a more favourable agro-political framework such as economic incentives for farmers, and participatory approaches in soil-related research and technology development focusing on soil management.

6.1 Conservation Tillage and Sustainable Soil Use

Conservation tillage generally refers to the maintenance of a cover of crop debris on the soil surface either to reduce the amount of tilling (reduced till or minimal till) or eliminate it altogether (no-till). However, due to regional, technical, economical and institutional differences, the term “conservation tillage” is understood differently in various parts of the world. The US Conservation Technology Information Center developed the first widely accepted definition of conservation tillage as “any tillage and planting system that covers at least 30% of the soil surface with crop residue, after planting, in order to reduce soil erosion by water" (CTIC 1999). Mannering and Fenster (1983) pointed out that "a common characteristic of any conservation tillage is its potential to reduce soil and water loss relative to conventional tillage." Conservation agriculture in Europe according to ECAF (1999) refers to "several practices, which permit the management of the soil for agrarian uses, altering its composition, structure and natural biodiversity as little as possible and defending it from degradation processes (such as soil erosion and compaction) and generally it includes any practice, which reduces, changes or eliminates soil tillage and avoids residue burning to maintain enough surface residue throughout the year."

Consequently, conservation tillage may be interpreted as "any system that boosts good crop yields while at the same time maintaining soil fertility, minimizing soil and nutrient loss, and saving energy-fuel inputs."

Wittmus et al. (1973) give a broad, well-accepted definition of conservation tillage as "tillage systems that create as good an environment as possible for the growing crop and that optimise the conservation of soil and water resources, consistent with sound economic practices,". In this context, the long-term impact of conservation-tillage practices can promote sustainable land use, improving nutrient availability and yield response.

Moreover, Fowler and Rockstrom (2001) pointed out that effective and acceptable conservation tillage must be identified and characterised in terms of soil, climate, and socio-economic conditions.

Long-term research on conservation tillage has been carried out for at least 30 years, especially in the semiarid and semi-humid regions with dryland farming, where it was concerned with crop production without supplemental irrigation. Many authors (Riley et al. 1994; Uri et al. 1998; Uri 2000; Hussain et al. 1999; Rasmussen 1999; Williams et al. 2005; Bravo et al. 2007, García et al. 2007) have reported several benefits for achieving sustainable land use from conservation-tillage systems: (1) economical benefits, i.e. labour, energy, machinery cost, and time saved, (2) positive effects in controlling soil erosion, and soil and water conservation, and (3) increases in soil organic matter.

Also, due to different weather and soil conditions, research has also reported low nutrient availability and inconsistent yield response with conservation tillage. In the USA for areas with low annual rainfall and on soils with low water-holding capacity (light, well-drained silty loam soils), it has been suggested that the positive aspects of conservation tillage outweigh the negative aspects. On land with drought stress and serious erosion problems, the added water should increase yield potential at more southern latitudes. Meanwhile moldboard plowing or chiselling often has the highest returns on dark, poorly drained silty-clay loams at northern latitudes, where the extra water may delay planting and reduce yield potential; and the lower temperature early in the growing season with surface residue systems could delay growth in the northern USA (Griffith et al. 1986).

However, Riley et al. (1994) reported some adverse effects of straw mulches on poorly drained soils, and poor results were found after early sowing on silt soil with reduced tillage, probably due to waterlogging at seed germination, with results in dry years being better than in wet years.

Studies have also documented potential benefits associated with conservation tillage: (1) potential carbon sequestration (Uri et al. 1998) with smaller C emissions due to slow oxidation under low temperatures with no-till; (2) potential nutrient availability where adequate fertilizer inputs were generally more critical with conservation-tillage systems (particularly no-till) than with conventional tillage systems and over the long term, requirements could decline as a result of accumulation and mineralization of soil organic matter (Rasmussen 1999); and (3) potential yield response, given that even though the crop yield with no-till was not usually reduced (Guérif et al. 2001), yields could be equivalent or higher compared to those from conventional tillage practices (Lindwall and Anderson 1981; Karunatilake et al. 2000).

In semi-arid regions under rainfed agricultural systems, water was the most limiting factor in crop production. Also crop yields with different tillage systems varied from year to year due to weather fluctuations. According to Lampurlanes et al. (2002) in terms of yields, the best tillage system is often a function of the weather that year. Durán et al. (2008) reported a reasonable almond yield in semiarid slopes under no-till with intermittent plant strips. Therefore, weather conditions in the growing season also appear influence the success of these systems. Eckert (1984) reported that non-tilled corn yielded more in drier than in normal years, whereas in the moderately well-drained soils of Ohio the yields with mouldboard plow were higher in wetter rather than in regular years. Hussain et al. (1999) also reported that no-till yields were 5–20% lower than with the moldboard plow in wet years, but were 10–100% higher in relatively dry years. Lal and Ahmadi (2000), after monitoring the effects of three tillage methods on maize yield in silty loam soil for 11 years in central Ohio, USA, found that there were no consistent trends in grain yields from year to year. However, a chisel-plow treatment outyielded no-till and mouldboard-plowing. Cantero et al. (1995) reported that in drought years, no-till had a yield advantage over the fully tilled fallow and blade plow tillage methods.

Due to regional differences in climate conditions and soils, there is no universal tillage or cropping system that is best for all situations. Nevertheless, changes in soil structure could affect the relative success of conservation tillage (Karunatilake et al. 2000). Studies in Canadian zones of black and grey soils, showed yield increases with no-till over conventional tillage from 0% to 23% for barley, spring and winter wheat, flax, canola and field pea (Lafond et al. 1996; Arshad et al. 1994; Borstlap and Entz 1994). In the north-central and north-eastern USA, weather and soil type strongly affected the relative success of reduced and non-tillage methods with fine-textured and poorly drained soils generally posing the greatest challenge to their adoption (Johnson and Lowery 1985; Lal et al. 1989; Cox et al. 1990). In Europe, according to Butorac (1994), it has been determined that well-drained soils, light to medium in texture with a low humus content, respond best to conservation tillage. The most obvious environmental advantage of reduced tillage is its role in minimizing erosion risks (Riley et al. 1994). Further expansion of conservation tillage on highly erodible land will result in a smaller impact on the environment and an increase in social benefits; nevertheless, the expected gains are likely to be modest (Uri et al. 1998).

Therefore, to develop sustainable land use, meet environmental quality, and allow for food-production needs (reducing the risk of yield failure) and provide a system that is integrated, applicable and advanced, technologies are needed to ensure successful acceptance and adoption of conservation methods. These include the need for better understanding of soil conservation and environmental protection, the need for better knowledge of the long-term impact of site-specific tillage practices, and the need to develop appropriate practical technologies.

6.2 Soil Biodiversity as the Key for Sustainable Soil Use in Agriculture

The feedback between soil C and atmospheric CO_2 is a process which is still not fully understood. However, it is generally accepted that the soil biota plays the dominant part in this complex interaction. Soil biological processes therefore can clearly have a strong effect on the global C cycle (Yoo et al. 2006; Bolinder et al. 2007). This is because soils contain approximately twice the amount of C as is found in the atmosphere, and fluxes totalling in the hundreds of giga-tonnes of C occur between the soil and the atmosphere on an annual basis (Schimel 1995).

In this context, Bellamy et al. (2005) found that an estimated 13 million t of C are lost from United Kingdom soils annually. This is the equivalent of 8% of total United Kingdom carbon emissions. As losses of soil organic carbon were found to be independent of soil properties, this has lead to the formation of the hypothesis that the stability of soil organic carbon depends on the activity and diversity of soil organisms (Schulze and Freibauer 2005). Studies at different latitudes have shown that the rate of soil organic matter decomposition doubles for every 8–9°C increase in mean annual temperature (Ladd et al. 1985). While this is greater than the predicted increases due to climate change, all other things being equal, it is apparent that increased global temperatures will speed up soil organic matter decomposition rates. This then has the potential to feedback into even greater losses of CO_2 from soil.

Soil biodiversity can also have indirect effects as to whether the soil functions as a C sink or source. It has been demonstrated repeatedly that soil biodiversity affects the erodibility of a soil due to a number of mechanisms including extracellular exudates, and physically binding soil particles together with fungal hyphae. This process is important with regard to climate change as it has been shown that soil erosion can turn soil from a C sink to a C source (Lal et al. 2008).

Today's society needs to recognise the need to restore and/or improve understanding: of the multiple goods and services provided by the different levels and functions of agricultural biodiversity; of the relationship between diversity, resilience, and production in agro-ecosystems; and of the impacts of traditional and newer practices and technologies on agricultural biodiversity as well as on the sustainability and productivity of agricultural systems. Special attention should be paid to the role of soil and other below-ground biodiversity in supporting agricultural production systems, especially in nutrient cycling.

Soil is a dynamic, living matrix that is an essential part of the terrestrial ecosystem. It is a critical resource not only to agricultural production and food security but also to the maintenance of most life processes (Hohl and Varma 2010).

Soils contain enormous numbers of diverse living organisms assembled in complex and varied communities. Soil biodiversity reflects the variability among living organisms in the soil ranging from the myriad of invisible microbes, bacteria, and fungi to the more familiar macro-fauna such as earthworms and termites. Plant roots can also be considered soil organisms in view of their symbiotic relationships and interactions with other soil components (Grayston et al. 1997; Nandasena et al. 2004). These diverse organisms interact with one another and with the various plants and animals in the ecosystem forming a complex web of biological activity. Environmental factors, such as temperature, moisture, and acidity, as well as anthropogenic actions (in particular, agricultural and forestry management practices), affect soil biological communities and their functions to different extents. In addition, according to Brussaard et al. (2007a), there is evidence that soil biodiversity confers stability under stress and disturbance, but the mechanism is not yet fully understood. It appears to depend on the kind of stress and disturbance and on the combination of stress and disturbance effects.

Soil organisms are an integral part of agricultural and forestry ecosystems; and they play critical roles in maintaining soil health, ecosystem functions, and production (Greenslade 1992; Park and Cousins 1995). Each organism has a specific role in the complex web of life in the soil:

1. The activities of certain organisms affect soil structure especially the so-called “soil engineers” such as worms and termites through mixing soil horizons and organic matter and increasing porosity. This directly determines vulnerability to soil erosion and availability of the soil profile to plants.
2. The functions of soil biota are central to decomposition processes and nutrient cycling (Paoletti et al. 1993). They therefore affect plant growth and productivity as well as the release of pollutants in the environment, for example the leaching of NO_3 into water resources.
3. Certain soil organisms can be detrimental to plant growth, for example, the build-up of nematodes under certain cropping practices. However, they can also protect crops from pest and disease outbreaks through biological control and reduced susceptibility (Grewal et al. 2005).
4. The activities of certain organisms determine the C cycle, the rates of C sequestration and gaseous emissions and SOM transformation (Carney and Matson 2005).
5. Plant roots, through their interactions with other soil components and symbiotic relationships, especially Rhizobium bacteria and Mycorrhiza, play a key role in the uptake of nutrients and water, and contribute to the maintenance of soil porosity and organic-matter content, through their growth and biomass (Duponnois et al. 2008).
6. Soil organisms can also be used to reduce or eliminate environmental hazards resulting from accumulations of toxic chemicals or other hazardous wastes. This action is known as bioremediation (Jasper 1994).

The interacting functions of soil organisms and the effects of human activities in managing land for agriculture and forestry affect soil health and quality (Park and Cousins 1995). Therefore, soil quality is the capacity of a specific kind of soil to function, within the boundaries of natural or managed ecosystems, to sustain plant and animal production, maintain or enhance water and air quality, and support human health and habitation. The concept of soil health includes the ecological attributes of the soil, which have implications beyond its quality or capacity to produce a particular crop. These attributes are chiefly those associated with the soil biota: its diversity, its food-web structure, its activity, and the range of functions it performs. Soil biodiversity per se may not be a soil property that is critical for the production of a given crop, but it is a property that may be vital for the continued capacity of the soil to support that crop (Andrén and Balandreau 1999; Dollacker and Rhodes 2007).

The sustained use of the earth's land and water resources and therefore plant, animal and human health is dependent upon maintaining the health of the living biota that provide vital processes and ecosystem services. However, current technologies and developmental support for increased agricultural production have largely ignored this fundamental management component. The improved management of soil biota could be key factor in maintaining soil quality and health and in achieving the goals of agricultural production and food security under sustainable land use and land-resource management.

Farming communities are concerned with land-management issues such as water availability to plants, access to sources of fuel and fodder, control of soil erosion and land degradation, especially avoiding soil nutrient depletion and pollution of air, soil, and water resources. At the global scale, the aggregated effects of these issues are embedded in the concerns of the international conventions on desertification, climate change, and biodiversity.

Nonetheless, farmers are essentially driven not by environmental concerns, but by economics, by issues of costs and returns, and thus efficiency in terms of labour and energy as well as the use of materials. A central paradigm for the farmer for the maintenance and management of soil fertility, without undue reliance on costly and often risky external inputs, is to undertake management practices in order to influence soil biological populations and processes in such a way as to improve and sustain land productivity. The means to create a more favourable environment within the soil and soil biological community for crop production involves site-specific decisions concerning crop selection and rotations, tillage, fertiliser and planting practices, crop residues and livestock grazing. These and many other factors influence ecological interactions and ecosystem function.

Capturing the benefits of soil biological activity for sustainable and productive agriculture requires a better understanding of the linkages among soil life and ecosystem function and the impacts of human interventions (Pankhurst and Lynch 1995; Doran and Zeiss 2000; Doran et al. 2002). The complex interaction among soil, plant and animal life, environmental factors, and human actions must be effectively managed as an integrated system (Pankhurst and Lynch 1995; Welch and Graham 1999). Greater attention to the management of soil biological resources –a hitherto neglected area in mainstream agriculture – will require a collaborative effort among scientists and farmers' and across ecological zones and countries, building on successful experiences.

The application of biotic indicators for evaluation of sustainable land use is applied on various levels, including the continental field as well as the individual agricultural enterprise (Osinski et al. 2003). Apart from the ecological evaluation of agricultural enterprises and agrarian policy measures, indicators are also used in environmental reporting and evaluation as well as in planning or simulation models in administrative and scientific fields. Already for a long period of time, indicators have been used as assessment criteria in landscape planning to make decisions regarding land use. Due to the standards the European Union commission requires from the member states in this regard, the application of indicators to assess the effects of agri-environment programs has gained prominence (Osinski et al. 2003).

6.2.1 The Benefits of Appropriate Soil-Biota Management

Soil organisms contribute a wide range of essential services to the sustainable functioning of all ecosystems. They act as the primary agents of nutrient cycling, regulating the dynamics of soil organic matter, soil-carbon sequestration, and greenhouse-gas emissions; modifying soil physical structure and water regimes, enhancing the amount and efficiency of nutrient acquisition by the vegetation and enhancing plant health. These services are not only essential to the functioning of natural ecosystems but constitute an important resource for sustainable agricultural systems (Andrén et al. 1999; Powell 2007). Direct and indirect benefits of improving soil biological management in agricultural systems include economic, environmental and food security benefits (Cassman and Harwood 1995; Pimentel 1998; Brussaard et al. 2007b) (Table 11).

The options whereby farmers can actually manage soil biodiversity to enhance crop production include indirect processes, such as composting or the control of pathogens, and direct interventions, such as microbial inoculation.

(i) Direct methods of intervening in the production system seek to alter the abundance or activity of specific groups of organisms through inoculation and/or direct manipulation of soil biota. Inoculation with soil beneficial organisms, such as nitrogen-fixing bacteria, Mycorrhiza and earthworms, have been shown to enhance plant nutrient uptake, bolster heavy-metal tolerance, improve soil structure and porosity, and reduce pest damage.

(ii) Indirect interventions are means of managing soil biotic processes by manipulating the factors that control biotic activity (habitat structure, microclimate, nutrients and energy resources) rather than the organisms themselves. Examples of indirect interventions include most agricultural practices such as the application of organic material to soil, tillage, irrigation, green manuring and liming, as well as cropping-system design and management. These must not be conducted independently, but in a holistic fashion, because of the recurrent interactions between different management strategies, hierarchical levels of management, and different soil organisms (Swift 1999).

Table 11 Benefits and impact from soil-biota management in agricultural systems

Benefits	Impacts
Economic	Appropriate soil-biota management reduces input costs by enhancing resource use efficiency (especially decomposition and nutrient cycling, N fixation and water storage and movement). Less fertiliser may be needed if nutrient cycling becomes more efficient and less fertiliser is leached from the root zone. Fewer pesticides are needed where a diverse set of pest-control organisms is active. As soil structure improves, the availability of water and nutrients to plants also improves. It is estimated that the value of "ecosystem services" (e.g. organic waste disposal, soil formation, bioremediation, N_2 fixation and biocontrol) provided each year by soil biota in agricultural systems worldwide may exceed US $ 1,542 billion (Pimentel et al. 1997).
Environmental	Soil organisms filter and detoxify chemicals and absorb the excess nutrients that would otherwise become pollutants when they reach groundwater or surface water. The conservation and management of soil biota help to prevent pollution and land degradation, especially through minimising the use of agro-chemicals and maintaining/enhancing soil structure and cation-exchange capacity. Excessive reduction in soil biodiversity, especially the loss of keystone species or species with unique functions, for example, as a result of excess chemicals, compaction or disturbance, may have catastrophic ecological effects, leading to loss of agricultural productive capacity.
Food security	Appropriate soil-biota management can improve crop yield and quality, especially through controlling pests and diseases and enhancing plant growth. Below-ground biodiversity determines resource use efficiency, as well as the sustainability and resilience of low-input agro-ecological systems, which ensure the food security of much of the world's population, especially the poor. In addition, some soil organisms are consumed as an important source of protein by different cultures and others are used for medicinal purposes. For example, in the Amazon basin, terrestrial invertebrates are used as food, and especially, as sources of animal protein, a strategy that takes advantage of the abundance of these highly renewable elements of the rainforest ecosystem (Paoletti et al. 2000).

Soil biota can have both positive and negative effects on agricultural production (Pankhurst et al. 2003; Weijtmans et al. 2009). Negative impacts often occur when soil-management systems are not well balanced with their environment. For example, inherent soil processes such as mineralization can no longer supply adequate amounts of nutrients for crop production because of long-term (continuous) removal, leaching, erosion, or volatilisation. Consequently, such biological processes have in many systems been supplemented by the use of commercially available inorganic nutrient sources. However, with decreasing SOM content, and associated properties such as water retention and cation-exchange capacity, the ability of the soil to retain nutrients and make them available as and when required, is significantly reduced. Thus, soil-quality or soil-health evaluations need to focus not only on chemical (fertility) considerations, but also on the dynamic soil condition – a combination of physical, biological and chemical characteristics – which is directly affected by recent and current land-use decisions and practices. Land managers can balance potential positive and negative impacts of their decisions on soil biota only through understanding the effects of individual components and their interactions within the agricultural system. This includes understanding the numerous and intricate interactions among climate, soil type, plant species and diversity, soil biological community, and soil-management systems.

The potential of using different components of soil biota and their activity as biological indicators has been cited by different authors. Such indicators include soil microbial biomass, soil enzyme activity, soil micro-fauna, including bacteria (eubacteria and archaebacteria), fungi, algae and plant-root pathogens, soil micro-fauna (protozoa, nematodes), macro-fauna, total soil biodiversity, etc. Soil organisms have been shown to be potentially useful indicators of soil health because they respond to soil management in time scales (months/years) that are relevant to land management (Pankhurst 1994). For example, changes in microbial biomass, or abundance of selected functional groups of micro-organisms, e.g. Mychorrizal fungi, may be detected well in advance of changes in soil organic matter content or other soil physical or chemical properties (Sparling 1997). One of the major difficulties in the use of soil organisms per se, or of soil processes mediated by soil organisms, as indicators of soil health has been methodological: what to measure, how and when to measure it, and how to interpret changes in term of soil function. Despite those difficulties, there have been major advances in our understanding of the soil biota and its functioning at the community level (Pankhurst et al. 1997).

There has been recent progress in acknowledging that soil health, by its broadest definition, is inseparable from issues of sustainability. The challenge ahead is to develop holistic approaches for assessing soil quality and health that are useful to producers, specialists, and policy makers in identifying agricultural and land-use management systems that are profitable and will sustain finite soil resources for future generations. The benefits of paying more attention to soil health and its assessment include its potential use in: the evaluation of land-use policy and of practices that degrade or improve soil resources; and in the identification of critical landscapes or management systems and of gaps in our knowledge base and understanding of sustainable management.

Soil biota provide key ecosystem services that are responsible for naturally renewable soil fertility, for mediating C sinks in the soil and many other functions. The conservation of healthy communities of soil biota and prudent use of specific soil organisms through biological soil management can be used to maintain and enhance soil fertility and ensure productive and sustainable agricultural systems (Matson et al. 1997). Moreover, the consequences of neglecting or abusing soil life will weaken soil functions, and contribute to greater loss of fertile lands and an over-reliance on chemical means for maintaining agricultural production.

6.3 Organic Farming for Sustainable Soil Use by Agriculture

Organic farming is a type of sustainable agriculture in which no synthetic pesticides or industrial fertilizers are used (MacCormack 1995; Rigby and Cáceres 2001). At organic farms, ecological balance is the abiding principle. Organic food is more than a trendy industry that provides healthful produce to co-ops and upscale markets.

The concept of sustainability has to date been very loosely applied to agriculture, so that to some it means ensuring profitability while to others it means wildlife protection (Rodiek and DelGuidice 1994; Rigby and Cáceres 2001). Only by taking a comprehensive view of what sustainable land management actually means will it be possible to develop a farming system which addresses all the issues; the issue is not just profit and wildlife but also resources and pollution, animal welfare, quality-food production, and health. Organic farming addresses all these issues, with success.

Reliance on legumes, particularly clover, for N fixation in the fertility-building phase of crop rotations and in pastures avoids the need for energy-consuming N fertilisers. This is the greatest factor contributing to a farming system that is more energy efficient on the basis of weight of food produced per hectare. Furthermore, the fact that N fertilisers are not used means that organic farming has a lower output of greenhouse gases and consequently has less impact on climate change.

Soil minerals are utilised more efficiently in organic farming; emphasis on encouraging soil biota and its ability to make nutrients more available, together with the avoidance of products that inhibit nutrient availability such as super phosphate, all contribute to a lower level of resource input, without any consequent depletion of soil reserves. Synthetic pesticides are prohibited in organic farming, avoiding chemical water pollution, with obvious benefits for drinking water and wildlife. Crop rotations which include 2 or 3 years of clover and grass ley will build soil organic matter, aid structure, act as a C sink and reduce soil erosion (Döring et al. 2005; Hole et al. 2005; Fließbach et al. 2007). Organic rotations reduce NO_3 leaching and consequent groundwater pollution due to the reduced cultivation and lower levels of N in the system. The effective storage and appropriate rates and timing of manure application that are a requirement of organic farming, minimize pollution risks. In addition, in recent years abundant research has been carried out on organic agriculture's effects on biodiversity (Youngberg et al. 1984; Isart and Llerena 1995; Van Elsen 2000).

The requirement to base organic livestock management on a health plan ensures that there is a properly planned strategy on stocking rates, breeding for health, natural rearing systems, spacious housing conditions and appropriate feeding regimes. Apart from this focus on management, organic livestock husbandry makes effective use of complimentary treatments such as homeopathy. It also puts animal medication firmly in its rightful place as an adjunct to good management, used only where necessary and never to enable over-intensification. All this results in the highest welfare standards, reduced reliance on medication and wormers, reduced antibiotic use, and consequently less risk of the building up of resistant strains of disease.

Mäder et al. (2002) reported results from a 21-year study of agricultural and ecological performance of biodynamic, bioorganic, and conventional farming systems in Central Europe, and showed that crop yields were 20% lower in the organic systems, although input of fertilizer and energy was reduced by 34–53% and pesticide input by 97%. Therefore, enhanced soil fertility and higher biodiversity found in organic plots may render these systems less dependent on external inputs.

6.3.1 Organic Farming and the Environment and Economy

Research on organic farming demonstrates numerous environmental benefits due both to active management of wildlife habitats and the natural consequences of the farming system (Rodiek and DelGuidice 1994; Rigby and Cáceres 2001; Hole et al. 2005; Fließbach et al. 2007):

- More abundant soil biota and bird populations due to the absence of pesticides and slug pellets
- Increased invertebrate, and therefore bird, populations resulting from the lower use of wormers
- Higher levels of beneficial wildlife species due to the encouragement of wildlife generally and natural predators in particular, and a more varied landscape
- Generally smaller fields and more spring-sown crops and a mix of arable land and grass leys
- Increases in soil organic matter, acting as a C sink
- Prohibition of the use of genetically engineered crops and products

Financial viability is fundamental to any farming system if it is to succeed in the commercial world. Especially those systems that have and important impact on rural economy (Lobley et al. 2009). Organic farming has developed an effective marketing scheme, establishing itself as the leader in the field of sustainability and appealing to a wide range of consumers willing to pay a premium for a quality product (Bourn and Prescott 2002; Roussos and Gasparatos 2009). It has done this through establishing a rigorous set of production standards which are inspected and accepted throughout the world. It has been able to compensate for lower yields and higher production costs by commanding higher prices and developing innovative marketing strategies

According to Haring et al. (2004), in the last 10–15 years the total organic production in Europe nearly tripled whereas approximately 4–5% of the total agricultural area is organically cultivated. Organic sales in Europe are growing in a food market still far from being satisfied and it offers great potential for providing the financial incentive to more farmers to adopt sustainable organic-farming methods (Bonny 2006). However, the market cannot be seen in isolation from conventional farming, which still receives governmental support that encourages unsustainable practices. Nor can it be seen in isolation from the positive drive to support wildlife conservation and environmentally friendly farming. In addition, Sauer and Park (2009) reported a positive relationship between subsidy payments and an increase in farm efficiency, technology improvements and a decreasing probability of organic market exit which was also confirmed for off farm income.

In developing countries organic farming is proving a viable proposition because it is less dependant on the purchase of inputs which are often not affordable by small farmers and it avoids the devastating health consequences of pesticides resulting from use without adequate information, education, or personal protection.

From the above, it is clear that organic farming already delivers on many key elements of sustainability, but the system as we know it has not yet found all the answers. Indeed, it as an evolving system and no one has demonstrated that it actually achieves sustainability. In practice, organic farming fails to deliver in several respects due in large part to the small amount of research and development that has gone into it compared with that for high input conventional agriculture.

This is not to dismiss the efforts of many others working to address the problems of sustainability where serious steps are being taken to change the farming approach – for example those using minimal cultivations or introducing new crop rotations which are not routinely dependant on pesticide inputs. Significant benefits can be achieved, albeit often only addressing a single issue in the process; for instance, a high standard of conservation management may be good for many species of wildlife, particularly those found in the non-cultivated areas of a farm but it does nothing to address the wider issues of sustainability.

Organic farming offers available system on which to build a sustainable future (Rigby and Cáceres 2001; Sandhu et al. 2008). Although there are many good aspects of organic farming systems, there are also negative ones as well, i.e., the control weeds in row crops such as corn, much more tillage is necessary, which can make organic farming much more prone to erosion in certain cases compared to regular no-till. However, it has been demonstrated that it is a system which farmers can adopt, it is successful, it produces good-quality, healthy food (i.e., vegetables and fruits), it is beneficial to biodiversity, and it reduces pollution risks. However, organic farming may gradually result in lower yields and indirectly induce an increase of the products' value. Most importantly it conserves soil quality and is working towards achieving a resource-conserving closed system. The biological, management, and systems approach offers the most robust basis for sustainable land management, and its implementation is essential.

7 Concluding Remarks

Sustainable use of land resources is of vital importance for the quality of human life and ultimately for human survival. Soil is becoming a scarce commodity and an object of competition among different sectors using it and this competition is growing. Such development will ultimately lead to land degradation and pollution of other resources, including ecosystems. The crucial and most important concerns to be addressed both politically and technically involve the search for sustainable solutions. The immediate answer is through drastic changes in the methods of using and managing land resources.

Failure to find the appropriate linkage between soil, food, and environmental security derives mainly from mismanagement. When addressing environmental security issues, there is a need to manage land resources more prudently, in quantity as well as quality, and reduce degradative pressures. Management of environmental parameters should be given a priority aimed at a better food supply, livelihoods and nature in a sustainable manner. Integrated approaches must be taken into account, not only scientific and technical ones, but also the socioeconomic and environmental aspects. A new generation of efficient land-use management systems should be designed while sustaining ecosystems and the environment. New technologies and management techniques will play an important role in meeting the challenge of demographic outburst and increased food demand. A tremendous gap still exists between research and its implementation.

In addition, new research is needed to design technologies that would conserve natural resources (particularly land) in a way which is environmentally friendly, technically appropriate, economically viable, and socially acceptable. This will be possible by rectifying management and usage practices of land resources allocated to the agricultural sector. Based on this review, a sustainable land-planning division should be created, one which would discourage undue encroachment on virgin land as well as in agricultural areas for environmental protection in order to seek balance and harmony between people and land.

Some reflections of this review paper in relation to sustainable soil management for building and maintaining healthy agricultural soils include:

- Delivering smarter agricultural land-use and natural-resource management in ways that make much more of an area’s economic potential
- Protects and renews soil fertility and the natural-resource base
- Integrates natural biological cycles and controls
- Optimises the management and use of on-farm resources
- Reduces the use of non-renewable resources and purchased production inputs
- Minimizes adverse impacts on health, safety, biodiversity, water quality, and the environment
- The soil should be covered to protect it from erosion and temperature extremes
- Mouldboard ploughing speeds the decomposition of organic matter, destroys earthworm habitats, and increases erosion
- To build soil organic matter in farming lands
- Reducing diffuse pollution and achieving more cost-effective management of water and soils
- Enabling rural and urban communities alike to enjoy a high quality of life based on their environment

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Drought Stress Effect on Crop Pollination, Seed Set, Yield and Quality

Ahmad M. Alqudah, Nezar H. Samarah, and Russell E. Mullen

Abstract The effect of drought stress on crop growth and yield has become more common worldwide in the last two decades. The reproductive stage is the most critical stage for drought stress during crop growth, because it strongly impacts yield and seed quality. Improving crop growth and yield under drought is thus a major goal of plant breeding. Drought stress negatively affects flower pollination by decreasing the amount of viable pollen grain, increasing the unattractiveness of flowers to pollinators, and decreasing the amount of nectar produced by flowers. Consequently crop seed set is lowered. Moreover, drought stress affects crop yield by reducing grain yield and all yield components. The correlation is clear between crop pollination, seed set and yield. Drought stress not only affects seed production, but also affects seed quality such as germination and vigor tests. In this chapter we review the currently available information on pollination, yield, and yield components and seed quality under drought. We give an outlook towards the physiological and biochemical processes involved in the reduction of crop yield in response to drought stress at the reproductive stage. We focus on physiological processes of plant reproductive organs in response to drought stress at anthesis and the attractiveness of the flowers to pollinators. Here we help plant breeders to select drought tolerant traits by understanding the correlations between pollination, yield, yield components and seed quality under drought stress at reproductive stage and to explain how drought stress effects final yield and seed quality during this stage.

Keywords Drought stress • Water deficit • Flower pollination • Seed set • Seed yield • Seed quality

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1 Introduction

The environmental stresses resulting from drought, temperature, salinity, air pollution, heavy metals, pesticides and soil pH are major limiting factors in crop production (Hernandez et al. 2001; Lawlor and Cornic 2002). Among others, drought stress is a main abiotic stress that limits crop production (Forster 2004). Drought can be defined as the absence of adequate moisture necessary for a plant to grow normally and complete its life cycle (Zhu 2002). Drought occurs every year in many parts of the world, often with devastating effects on crop production (Ludlow and Muchow 1990). Worldwide losses in crop yields from drought stress probably exceed the losses from all other abiotic stresses combined (Barnabas et al. 2008). Because water resources for irrigating crops are declining worldwide, the development of more drought-resistant or drought-tolerant cultivars and greater water-use efficient crops is a global concern (Ludlow and Muchow 1990). In the last several decades, the most productive agricultural regions were exposed to drought stress in most years and in occasional years with severe drought. Commonly, drought stress synchronizes with extreme temperature, leading to even greater severity of drought stress (Barnabas et al. 2008).

Drought stress affects crop growth and yield during all developmental stages. The effect of drought on yield is highly complex and involves processes as diverse as reproductive organs, gametogenesis, fertilization, embryogenesis, and seed development stress (Barnabas et al. 2008). Reproductive development at the time of flowering is especially sensitive to drought stress (Zinselmeier et al. 1995, 1999; Samarah et al. 2009a, b). Therefore, an understanding of how a reproductive process affected by drought is of particular interest for improving drought tolerance (Samarah et al. 2009a, b). During flowering early crop yield potential, i.e. the number of grains per land area, is determined. Final crop yield is primarily determined by resource availability and the number of grains is adjusted in the plant to match the resource-defined yield level (Sinclair and Jamieson 2006). Manipulation of flowering time might also have considerable significance as a management tool to avoid yield reductions that might commonly occur from drought stress during anthesis in a growing region (Tewolde et al. 2006).

Improvements in seed yield must be a result of underlying physiological changes in crop plants. Physiological changes are interpreted here in the broadest sense as any change to the growth, development, morphology, anatomy or physiology of a crop. Nevertheless, a physiological change such as flowering time has been important for yield progress and for breeders to effectively select for desirable trait expression to maintain crop adaptation and optimal yield. Flowering time has been particularly important for yield improvement in water-limited environments (Richards 1991). In this environment, flowering must not only be early enough to escape the detrimental effects of early drought on flower set but tolerant enough to reach maximum seed yield during later drought. It is clear that drought induces structural, physiological and molecular abnormalities in the processes leading to the development of gametes. These abnormalities can greatly influence the success of fertilization because of the production of dysfunctional male and female gametophytes, even if fertilization took place under optimum environmental conditions.

The flowering period of a crop is a critical growth stage and a yield determinate factor in normal growing seasons and in drought stressed regions in particular. An understanding of how crop plants respond to drought stress during reproductive stage is important in maximizing yields in water-limited regions. In regard of the effect of drought at reproductive stage on seed quality, this is no much information available. Most of reported research on the effect of drought on seed quality has been on plants exposed to drought stress during seed filling stage. In this chapter, we summarized the current research and findings related to the effect of drought on pollination, attractiveness of flowers to pollinators, yield, yield components and seed quality. The physiological changes in the reproductive organs in plants exposed to drought stress during anthesis are also discussed.

2 Effect of Drought Stress on Crop Pollination

2.1 Effect of Drought on Pollen Grain Viability

Drought stress is a main abiotic stress that limits crop pollination by reducing pollen grain availability (Agren 1996; Trueman and Wallace 1999), increasing pollen grain sterility (Schoper 1986; Al-Ghzawi et al. 2009), decreasing pollen grain germination and pollen tube growth (Lee 1988). Drought stress can also reduce megagametophyte fertility (Young et al. 2004), inhibit the differentiation of young microspores (Satake 1991), lower the number of dehisced anthers (Sawada 1987), repress anther development (Nishiyama 1984), and decrease seed set and seed development (Al-Ghzawi et al. 2009).

The viability of maize pollen is related to its water content and to the drying conditions of the atmosphere (Buitink et al. 2002). The relative water content of corn pollen affects pollen speed and survival (Aylor 1999). Drought stress has induced adverse effects on male gametophyte development resulting in fewer numbers of viable pollen in rice (Sheoran and Saini 1996). A rapid pollen germination (after 5 min) has been reported for many plant species, e.g. *Brassica Oryza sativa* L. (Wang et al. 2000), *Cucurbita pepo*, *Parietaria judaica*, *Zea mays* (Pacini 2000), due to the pollen rapid imbibitions (Pacini 2000). In a review article, Saini and Westgate (2000) highlighted evidence for physiological and hormonal signals emanating from the parent plants, especially carbohydrate availability and metabolism, as well as hormonal based signal. In wheat, barley, and rice, Abscisic acid (ABA) was implicated as a cause of pollen sterility (Boyer and Westgate 2004). In maize, the decrease in the sugar stream due to losses in photosynthetic rate under drought stress appeared to be critical for the development of the female inflorescence (Boyer and Westgate 2004). Artificially feeding sucrose to the stems in maize at low water potentials can prevent many ovaries from aborting (Boyle et al. 1991;

Zinselmeier et al. 1995, 1999), indicating that drought stress may decrease seed set by increasing ovary abortion due to lowering the photosynthate supply to ovaries during their development. In other studies sucrose artificially fed to replace the photosynthate missing during the exposure to low water potentials overcome the negative effect of drought (Zinselmeier et al. 1995, 1999).

Starch is considered a major energy source for pollen development and germination (Clément et al. 1994), hence the absence of this energy source could lead to pollen sterility. The level of starch has been reduced in anthers from plants exposed to water stress (Sheoran and Saini 1996). The carbohydrate content in maize can also be low enough to limit silk osmotic adjustment (Westgate and Boyer 1985a). Because of the disturbances in the carbohydrate metabolism, the internal pollen wall, which consists of pectocellulose, is unable to develop normally and insufficient amounts of reserve nutrients (starch) are stored in the cytoplasm of vegetative cells in the pollen grains (Sheoran and Saini 1996). Under drought stress, stored carbohydrates may become the predominant source of transported materials, contributing as much as 75–100% to the grain yield (van Herwaarden et al. 1998). This phenomenon raised an interesting hypothesis about the potential competition for hydrolyzed carbohydrates between the vegetative organs and the grain for the purposes of osmotic adjustment and starch synthesis, respectively (Plaut et al. 2004).

Pollen grain is sensitive to drought stress because it’s early stage in reproductive growth and its need sufficient water and energy to complete growth/development process. Drought stress affects on pollen grain viability by blocking the process of pollen grain germination and development (Lee 1988). This process is also affected by the increase in level of ABA and limiting sources of energy such as sugar, starch and carbohydrate under drought stress (Boyer and Westgate 2004). All of these factors lead to increase the number of pollen grain sterility, abnormal pollen grain and pollen grain abortion.

2.2 *Effect of Drought on Ovary Development*

Increasing evidence indicates that ovary abortion can account for substantial kernel losses when maize experiences low water potential near the time of pollination (Westgate and Boyer 1985b, 1986; Boyle et al. 1991; Zinselmeier et al. 1995, 1999; Andersen et al. 2002). The failure of silks to elongate can lead to the completion of pollen shed before silks emerge, which and consequently decreases kernel numbers (Herrero and Johnson 1981). When maize plants are exposed to drought stress, silks may prematurely dry reducing pollination and consequently reducing the capability of the pistillate flower to produce seeds (Schoper et al. 1986). In soybean, ovary abortion was caused by only 2 or 3 days of low water potential, which was enough to inhibit leaf photosynthetic rates (Westgate and Boyer 1986).

Several studies have reported that ovary abortion under drought stress was related to breakdown of ovary starch (Zinselmeier et al. 1999; Andersen et al. 2002) or the delivery mechanisms of sugars more than the release mechanisms of sugars from the carbohydrate reserves in the parent plants. Acid invertase, the main enzyme to process sucrose, had less activity at low water potential than at high water potential (Zinselmeier et al. 1995; Zinselmeier et al. 1999; Andersen et al. 2002). Acid invertase activity was not fully restored by feeding sucrose to the stems (Zinselmeier et al. 1999), suggesting that moisture stress and invertase activity may be influenced by each other and not just indirectly through photosynthetic supply of sugar. Intermediates for starch biosynthesis downstream of the invertase step were depleted at low water potential and not fully restored by the sucrose feeding (Figs. 1 and 2), which implicated acid invertase as a limiting step in starch biosynthesis (Zinselmeier et al. 1999).

Development of the ovary is one of the most vulnerable phases in response to drought stress (Boyer and Westgate 2004) and it's very sensitive to insufficient energy sources. The accumulation of non-reducing sugars and the failure of starch accumulation affects on ovary development. Failure of silks elongation, abnormality and ovary abortion are the main result from limited energy sources in this phase.

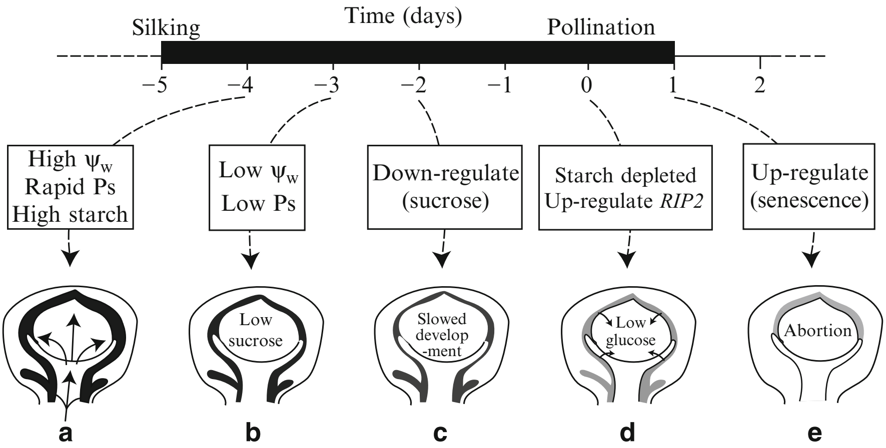

Fig. 1 Summary of events leading to abortion of maize ovaries when plants are subjected to low water potential around the time of pollination. (**a**) Photosynthesis providing sucrose to give about 1 mg of dry mass on the day of pollination to ovaries containing 3 mg of dry mass. About 0.4 mg of the dry mass is starch shown as black area in ovary wall. (**b**) Low water potential enough to inhibit photosynthesis curtails sucrose delivery. (**c**) Genes for sucrose processing are down-regulated. (**d**) Lack of sucrose triggers starch breakdown, maintaining glucose for a short time. About the time glucose concentrations fall, RIP2 is up-regulated. (**e**) With a continued lack of glucose, certain senescence genes are up-regulated, leading to irreversible loss in development. (Image is taken from McLaughlin and Boyer 2004).

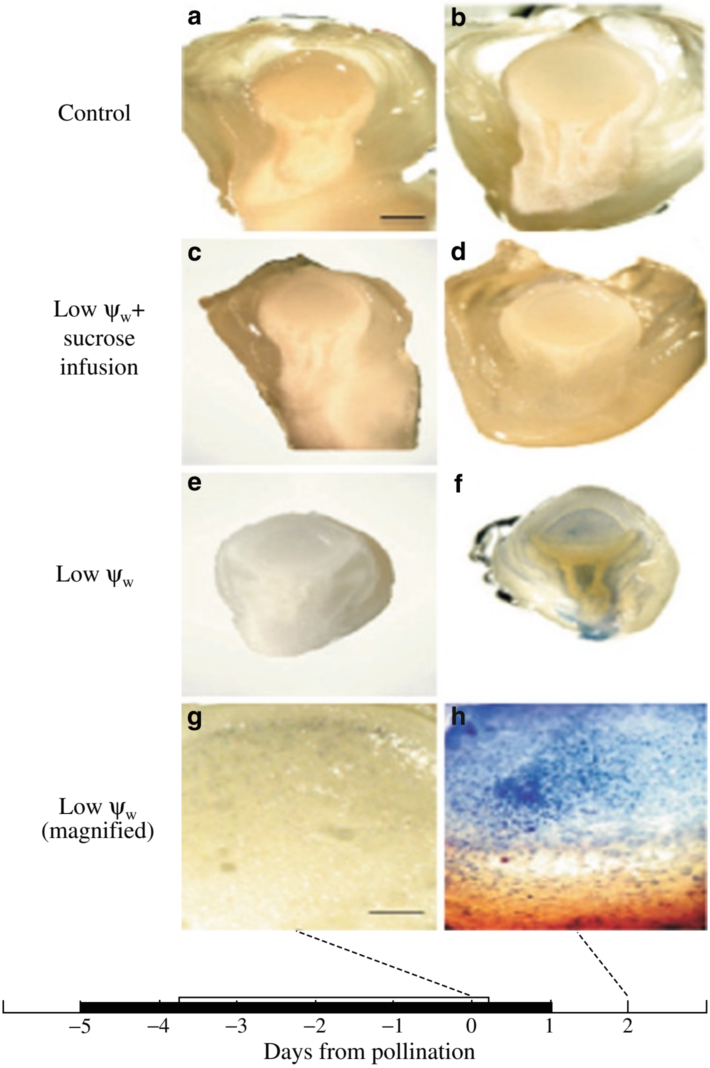

Fig. 2 Evans Blue staining of maize ovaries when low water potential occurred around the time of pollination. Control: high water potential (**a** and **b**). No stain visible. (**c** and **d**) Low water potential plus sucrose infusion. No stain visible. (**e** and **f**) Low water potential. No stain detectable in (**e**) but stain is apparent in (**f**). Stain in (**f**) is present in nucellus and around vascular tissue in upper pedicel 2 day after pollination. (**g** and **h**) Magnified view of nucellus in (**e** and **f**). No stain detected in (**g**) but present in individual cells in (**h**). The black bar on the abscissa indicates when water was withheld from the soil. Plants were rewatered on day 0. The white bar indicates when sucrose was infused into stems starting on day 4 and continuing each day to include day 0. Scale bars: a–f = 1 mm; G and H = 0.1 mm. Image is taken from McLaughlin and Boyer 2004.

2.3 Effect of Drought on Flower Characteristics

Flowering is one of the most important growth stage affected by drought stress. Drought stress interferes with flower period, flower opening, nectar production, and turgor maintenance of floral organs (Mohan Ram and Rao 1984). The trend for reduced flower size under drought stress is mirrored in populations of *Clarkia unguiculata* distributed along a natural moisture gradient (Jonas and Geber 1999). Water stress detrimentally affects flower induction, pollen production and subsequently leads to failure of fertilization and hence grain set (Sheoran and Saini 1996). Water stress during flower induction and inflorescence development leads to a delay in flowering (anthesis), or even complete inhibition of flowers (Wopereis et al. 1996; Winkel et al. 1997). Craufurd and Peacock (1993) have reported a delay in flower initiation caused by water stress in species of *Pennisetum* and *Sorghum*. Very few studies have been done to determine the effects of drought on the process of floral induction in cereals per se, which is difficult to separate from post-induction floral development in many cases (Saini and Westgate 2000). Drought stress reduces mean petal size, nectar secretion and pollen production in flowers of *Raphanus raphanistrum* (Strauss et al. 1996).

The magnitude of flower abortion varies with the position on the plant, being greater in the branches, the lower part of the main stem and the top nodes of the main stem (Wiebold et al. 1981). In soybean, within individual racemes, the proximal positions exhibit a higher pod-set percentage than do the distal positions (Kokubun and Honda 2000). Decreased photosynthetic rate might have reduced the allocation of assimilates to reproductive organs, which could have been a reason for the increased rates of flower abortion in water-deficient plants, as indicated by Raper and Kramer (1987).

The appropriate matching of the pattern of flower/inflorescence development, the time of flowering, flowering opening and period to the temporal variation in water availability is recognized as one of the most important traits conferring adaptation to drought (Bidinger et al. 1987; Passioura 1996). The effects of drought on floral meristems (induction and initiation) are among the least understood aspects of crop reproductive development under water-limited conditions. Drought stress leads to a delay in flowering (anthesis), accelerate flower/inflorescence growth, development and abortion.

2.4 Effects of Drought on Flower Attractiveness to Pollinators and Nectar Production

Flower attractiveness to pollinators can be negatively affected by drought stress, which could be attributed to many factors (Al-Ghzawi et al. 2009). Drought stressed flowers may have different food-based cues which decrease foraging made by honeybees (Pernal and Currie 2002). The time required for flower development under drought stress was less than the time usually required by normal plants (Al-Ghzawi et al. 2009), which might reduce flower size and nectar production (Zimmerman and Pyke 1988; Lee and Felker 1992; Campbell 1996) and nectar sucrose content (Wyatt et al. 1992). Non-stressed flowers produced with supplemental watering increased nectar volume in *Delphinium nelsonii* (Zimmerman 1983), *Polemonium foliosissimum* (Zimmerman and Pyke 1988), and *Asclepias syriaca* (Wyatt et al. 1992) and increased nectar sucrose content in *Asclepias syriaca* (Wyatt et al. 1992), which were cues that attract pollinators. Comparisons between growing seasons that differ in precipitation also suggested that nectar production by *Prosopis landulosa* (Lee and Felker 1992) and by *Ipomopsis aggregate* (Campbell 1996) was greater in wet years than in dry years. In support of this finding, McLaughlin and Boyer (2004) reported that glucose, an immediate product of sucrose hydrolysis by invertase, was depleted in ovaries undergoing abortion at low water potential. The prevention of abortion with exogenous sucrose applications observed by Boyle et al. (1991) and Zinselmeier et al. (1995, 1999) suggests that certain abortion-inducing genes could be sugar-responsive. Koch (1996) and Sheen et al. (1999) identified a number of sugar responsive genes in plants. Water availability had little effect on nectar sugar concentration (Wyatt et al. 1992; Campbell 1996). Nectar production also depended on plant age in natural populations of *Lobelia cardinalis* (Devlin et al. 1987). A similar pattern of pollinator behavior would be expected for plants of *E. angustifolium* under drought stress, especially because bumble bees preferentially visit and remain longer at fireweed flowers with enriched nectar volume (Galen and Plowright 1985).

Well-watered plants were reported to produce much more nectar and pollen (Zimmerman and Pyke 1988) and were characterized by increased nectar sucrose (Wyatt et al. 1992). Bees normally fly to flowers that produce abundant nectar and pollen under drought stress (Al-Ghzawi et al. 2009). Boose (1997) found that clones of *Epilobium canum* produced less nectar when watered every other day with approximately half the amount of water that the control plants received daily. The attractiveness of plant species to pollinators depend on flower and nectar characteristic (Al-Ghzawi et al. 2009) such as flavor, color, nectar volume, sugar concentration and aroma. The attractiveness is important to ensure the successful transport of pollens to the stigmas of pistilate flowers by bees during nectar collection. Insect pollination regularly contributes to the increase in plant seed set (Al-Ghzawi et al. 2009). The persistence of less attractive flowers may be partially explained by selective pressures of the abiotic environment on floral traits (Campbell 1996). Al-Ghzawi et al. (2009) reported that drought stress imposed during flowering stage affects on visitation number, number of inflorescences and flowers, pollen grain weight, viability of pollen grain and seed set for *Trigonella moabitica* in Jordan. They also reported that wild bees had more number of visitations to flowers grown under severe drought stress than honeybees (Al-Ghzawi et al. 2009).

Flower attractiveness to pollinators depends on nectar quality/quantity and type of visitor. Nectar quality/quantity (flavor, color, nectar volume, sugar concentration and fragrance) are adversely affected by drought stress, this leads to reduce number of bees visitings to flower and reduce amount of nectar produced. Wild bees can adapt with flower exposed to drought stress and visit it more than honeybees (Tables 1 and 2).

Table 1 Effects of drought stress on pollination traits

Pollination traits	Effects related to drought	References
Pollen grain availability	Decrease number of pollen grain availability	Agren 1996; Trueman and Wallace 1999; Sheoran and Saini 1996
Pollen grain sterility	Increase number of pollen grain sterility	Schoper 1986; Al-Ghzawi et al. 2009
Pollen grain germination and pollen tube growth	Decrease number of pollen grain germination and reduce pollen tube growth	Lee 1988; Pacini 2000
Megagametophyte fertility	Decrease megagametophyte fertility	Young et al. 2004
Young microspores	Inhibit young microspores	Satake 1991
Dehisced anthers	Decrease number of dehisced anthers	Sawada 1987
Anther development	Decrease anther development.	Nishiyama 1984
Ovary abortion	Increase number of ovary abortion	Westgate and Boyer 1986
Ovules fertilized and developed	Decrease number of ovules fertilized and developed	Boyle et al. 1991; Zinselmeier et al. 1995, 1999; Andersen et al. 2002
Silks to elongation	Reduce silks to elongate	Herrero and Johnson 1981
Flower size	Reduce flower size	Jonas and Geber 1999
Flower induction	Detrimentally flower induction	Sheoran and Saini 1996
Flower induction and inflorescence development	Delay in flowering (anthesis), or even complete inhibition	Wopereis et al. 1996; Winkel et al. 1997
Flower attractiveness	Decrease flower attractiveness	Al-Ghzawi et al. 2009

Table 2 The role of biochemical contents in response to drought stress

Biochemical contents	Effects related to drought	References
Abscisic acid (ABA)	Increase pollen sterility, ovary abortion and inhibits cell division in the embryo	Boyer and Westgate 2004; Liu et al. 2005; Setter and Flannigan 2001
Sugar	Important for development of the female inflorescence	Boyer and Westgate 2004
Artificially feeding sucrose	Can prevent many ovaries from aborting and replace the photosynthate missing	Boyle et al. 1991; Zinselmeier et al. 1995, 1999
Starch	Major energy source for pollen development and germination	Clément et al. 1994
Carbohydrate	Silk osmotic adjustment	Westgate and Boyer 1985a
Acid invertase	The main enzyme to process sucrose	Zinselmeier et al. 1995, 1999; Andersen et al. 2002

3 Effects of Drought on Seed Set

Drought stress is a main constraint to agricultural production including terminal stresses observed in low rainfall areas of the world. The abortion of potentially viable immature seeds and fruits between anthesis and dispersal has gained increased attention from plant ecologists during the last two decades. Soil water deficits that occur during the reproductive growth are considered to have the most adverse effect on crop yield (Costa-Franca et al. 2000; Samarah 2004; Samarah et al. 2009a, b). Drought stress imposed on plants leads to decrease yield through reducing seed set (Westgate and Boyer 1986; Al-Ghzawi et al. 2009). Low seed set percentages are regularly related to several factors such as reducing pollen grain availability (Agren 1996; Trueman and Wallace 1999), increase ovary abortion (Boyer and Westgate 2004), increase pollen grain sterility (Schoper 1986; Westgate and Boyer 1986; Al-Ghzawi et al. 2009), slow stigma and style elongation (Westgate and Boyer 1985b), reducing time of pollination (Westgate and Boyer 1986), lower pollen grain germination activity, pollen tube growth, and less development of fertilized seeds (Lee 1988). A clear correlation between seed set and limitation of resources and pollen availability has been demonstrated (Trueman and Wallace 1999). Water deficit in the meiotic stage also reduced grain set in self-pollinated wheat (Saini and Aspinall 1981) and rice (Sheoran and Saini 1996).

Grain yield and seed set reductions in small grains under drought stress are likely due to ovary abortion or pollen sterility (Boyer and Westgate 2004). An increase in Abscisic acid content in the generative organs is one of the factors suggested to play a role in seed abortion and yield reduction in response to drought stress (Liu et al. 2005). In soybean, pod set was positively correlated with photosynthetic rate and negatively correlated with the Abscisic acid in pods (Liu et al. 2004). Elevated Abscisic acid content in crop reproductive structures positively associated with kernel/pod abortion, presumably via inhibition of cell division in the young ovaries (Liu et al. 2003; Setter et al. 2001). In addition, exogenous application of Abscisic acid to developing maize ovaries inhibited cell division in the embryo and endosperm, and this effect was probably due to a depression of cell cycle gene expression by high levels of Abscisic acid (Setter et al. 2001). On the other hand, Selote and Khanna-Chopra (2004) suggested that high levels of Reactive Oxygen Species (ROS) and an inefficient anti-oxidant system in the panicle may be the cause of drought induced spikelete sterility in rice. Similarly, enhanced anti-oxidative activities have been shown to confer better drought tolerance in wheat (Sairam and Saxena 2000). Other reports have also demonstrated that the involvement of programmed cell death and oxidative stress resulted in pollen sterility on Cytoplasmic Male Sterility (CMS) in rice (Li et al. 2004; Jiang et al. 2007; Wan et al. 2007).

Pod number per plant at maturity is a main yield determinant in soybean (Dybing et al. 1986). Drought stress occurring during flowering and early pod development significantly increased the rate of pod abortion and consequently decreased final seed yield of soybeans (Westgate and Peterson 1993; Liu et al. 2003).

Reproductive potential in soybean may be due to considerably reduced abscission of developing flowers and pods soon after anthesis during pro-embryo development [3–5 day after anthesis (DAA)] (Peterson et al. 1990) even under optimal environmental conditions. This stage is one of active cell division in the young ovules, coinciding with a rapid pod expansion (Peterson et al. 1992), which is particularly sensitive to drought stress (Westgate and Peterson 1993). Experimental evidence from cereals (e.g. maize) and grain legumes (e.g. lupine) has suggested important roles of the factors in regulating kernel/pod set under drought conditions (Palta and Ludwig 1997; Saini and Westgate 2000; Setter et al. 2001). In cereals, several lines of evidence have suggested that drought-induced large concentrations of Abscisic acid in the reproductive structures exert a negative effect on fruit/seed set (Westgate and Boyer 1986; Setter et al. 2001). In soybean, Liu et al. (2004) showed that ABA in flowers and pods was increased by drought stress and was associated with a reduction in pod set. These studies suggest that drought stress leads to increase ABA concentration causing pod abortion. Liu et al. (2004) found that ABA affected pod set directly via the processes within the ovary (i.e. cell division) or indirectly via influencing the availability of photosynthate sugar. A similar argument had been previously raised for seed abortion in wheat (Waters et al. 1984).

Charles-Edwards et al. (1986) suggested that number of seeds per plant of soybean was positively and linearly correlated with leaf photosynthetic rate. This hypothesis was supported by the work of Egli and Yu (1991) and Jiang and Egli (1993) using source–sink manipulations. On the other hand, several studies have shown that water deficits imposed during the reproductive development of dry beans can decrease number of flowers and pods per plant and number of seeds per pod (Loss and Siddique 1997). Pod abortion in soybean under drought stress has been observed in a range between 21% and 65% (Mwanamwenge et al. 1999). In general, number of pods per plant seems to be the most yield component affected by drought stress during flowering and can reduce final grain yield up to 70% depending on the duration and intensity of the stress period (Lopez et al. 1996).

Another possible mechanism by which severe-drought stress reduced seed set is by reducing the expression of the soluble acid invertase (*Ivr2*), which decreases the hexose-to-sucrose ratio in ovaries (Andersen et al. 2002). Pre-anthesis stem reserve accumulation could be another potential factor that determines seed number under drought stress. In wheat, pre-anthesis stem reserve accumulation is considered to be a significant factor affecting flower and grain development under stress conditions (Blum 1998). Water shortage results in inhibitions in the photosynthetic processes causing reductions in nutrient supply (sucrose) to the reproductive organs (Campbell 1996). An insufficient supply can block the development of reproductive structures and cause kernel abortion (Westgate and Boyer 1986). Large amounts of carbohydrate were moved from the stems to the grain that made up for the lack of current photosynthesis (Westgate and Boyer 1985a). As a result, there was often a relationship between the dry matter in the grain at the end of the season and that in the parent (Yang et al. 2001).

Seed set is affected by all development and growth processes in reproductive stage such as pollen grain and ovary development under drought stress. It's strongly correlated with yield, e.g. final number of seeds per kernel is one of the indicator for seed set percentage. Also, it's sensitive to biochemical contents such as ABA and energy sources. Inadequate energy source such as sugar and increase level of ABA leads to reduce seed set percentage by increase number of seed abortion and abnormality (Liu et al. 2004).

4 Effects of Drought on Seed Yield

Many researchers have found that the reduction in number of spikes per plant under drought stress was due to the increase in the number of sterile spikes per plant and the decrease in the number of fertile spikes per plant in six-row barley (Mogensen 1992; Sanchez et al. 2002; Samarah 2004; Samarah et al. 2009a). A reduction in number of grains per spike has been reported for barley (Agueda 1999; Mogensen 1992; Samarah 2004; Samarah et al. 2009a) and wheat (Garcia 2003) under drought stress. Otegui and Slafer (2004) reported that the grain number in wheat was primarily determined by the number of fertile florets, while in maize, a monoecious crop, the critical step was grain set, which depended on the success of fertilization. Low water potential near the time of pollination decreased the ratio of yield to dry matter because kernel numbers diminished (Boyer and Westgate 2004).

The individual grain weight in cereals was also reduced by drought stress, which could be attributed to shorter grain filling duration and lower accumulation of dry matter in the growing kernels (Agueda 1999; Sanchez et al. 2002; Garcia 2003; Samarah 2004; Samarah et al. 2009a) or as a result of the reduction in the rate and duration of starch accumulation in the endosperm (Brooks et al. 1982). Samarah (2004) reported that the developing grain from barley plants grown under mild- and severe-drought stress treatments had lower grain weight and a faster loss of grain moisture content that those from the well-watered plants.

Declines in total grain yield under the drought stress treatments are due to the reduction in grain yield components, such as grain number per spike (Agueda 1999; Garcia 2003; Samarah 2004; Samarah et al. 2009a), and spike number per square meter (Agueda 1999; Sanchez et al. 2002; Garcia 2003; Samarah et al. 2009a) and individual grain weight (Mogensen 1992; Samarah et al. 2009a).

Grain set and consequently grain number were highly correlated with grain yield in barley (Samarah 2004). Yield loss in chickpea due to inadequate soil moisture availability varied between 36% and 42% depending on geographic location and climatic condition during the crop season (Saxena et al. 1993). Grain yield reductions ranging from 20% to 70% of the control have been observed in rice under water-deficit treatment during the reproductive stage (Lilley and Fukai 1994). Full supplementary irrigation increased chickpea yield by 65% (Oweis et al. 2004) and by 100% (Zhang et al. 2000) as compared with rainfed conditions. However, the 2/3 supplementary irrigation of chickpea level resulted in optimum water use efficiency

Table 3 Effects of drought stress on yield and yield components traits

Yield traits	Effects related to drought	References
Grains per spike	Decrease number of grains per spike	Agueda 1999; Mogensen 1992; Garcia 2003; Samarah 2004; Samarah et al. 2009a
Fertile florets	Decrease number of fertile florets	Otegui and Slafer 2004
Fertile spike per plant	Decrease number of fertile spike per plant	Mogensen 1992; Sanchez et al. 2002; Samarah 2004; Samarah et al. 2009a
Sterile spikes per plant	Increase number of sterile spikes	Mogensen 1992; Sanchez et al. 2002; Samarah 2004
Spikes per plant	Decrease number of spikes per plant	Mogensen 1992; Sanchez et al. 2002; Samarah 2004; Samarah et al. 2009a
Individual grain weight	Decrease weight of individual grain	Mogensen 1992; Agueda 1999; Sanchez et al. 2002; Garcia 2003; Samarah 2004; Samarah et al. 2009a
Grain yield	Decrease grain yield	Agueda 1999; Garcia 2003; Samarah 2004; Samarah et al. 2009a
Spike number per square meter	Decrease spike number per square meter	Agueda 1999; Sanchez et al. 2002; Garcia 2003; Samarah et al. 2009a
Straw yield	Decrease straw yield	Agueda 1999; Sanchez et al. 2002; Garcia 2003; Samarah 2004; Samarah et al. 2009a
Harvest index	Decrease harvest index	Ekanayake et al. 1989; Samarah et al. 2009a

(Oweis et al. 2004). Limited supplemental irrigation can play a major role in increasing and stabilizing the productivity of spring-sown chickpea (Soltani et al. 2001). Water stress during flowering may reduce the harvest index by 60%, largely due to reduction in grain set (Ekanayake et al. 1989). There was a significant correlation ($P<0.001$) between water use and seed yield of chickpea ($R^2=0.75$) (Anwar et al. 2003).

Drought stress during reproductive stage reduced crop yield by decreasing seed yield and yield components. The reduction in crop yield under drought stress could be due to the accelerated days to flowering, shorter grain filling duration and lower accumulation of dry matter. The increase in number of sterile floret and spike is the main result from drought stress and it's correlated with seed set percentage (Table 3).

5 Effect of Drought Stress on Seed Quality

Drought stress not only affects seed production, but many researchers found that drought stress during reproductive growth lowered seed germination and vigor. Seed quality, estimated by standard germination, was lower for seeds harvested from plants grown under drought than seeds harvested from irrigated plants (Drummond et al. 1983). Smiciklas et al. (1992) reported that drought stress at beginning of seed fill (R_5) reduced seed germination percentage, seedling dry weight, and increased the electrical conductivity of seed leachate. The reduction in germination percentage under the stress was approximately 9% compared with non-stressed plants (Smiciklas et al. 1992). Abnormal seedlings represented the majority of the non-germinated seeds that were obtained from drought-stressed plants (Smiciklas et al. 1989). Drought stress imposed on soybean during seed fill (R_5) decreased standard germination by 5%, seed vigor, as estimated by the decrease in seedling dry weight, by 12%, and an increase in electrical conductivity of seed leachate by 19% (Dornbos and Mullen 1985). In four field experiments conducted at Stoneville, Mississippi, using soybean maturity groups IV, V, and VI, Heatherly (1993) reported that non-irrigated plants produced seeds with low standard germination (less than 70%) in all experiments when irrigation was withheld at different periods during reproductive growth (R_1 to R_6). Irrigation (from flowering through seed fill) was required to improve seed germination in all experiments (Heatherly 1993).

Other researchers reported that drought stress during seed development reduced seed vigor but had no effect on seed germination (Yaklich 1984; Fougereux et al. 1997; Iannucci et al. 1996, Samarah and Alqudah 2009). Drought stress during soybean pod fill reduced seed vigor, as measured by the accelerated aging test, but had no effect on lab and field emergence (Yaklich 1984). A reduction in seed vigor, estimated by electrical conductivity and cold tests, was observed in pea seeds obtained from plants exposed to drought stress during the entire reproductive period, but seed germination was not affected (Fougereux et al. 1997). They reported that the decrease in seed quality was higher when drought stress occurred during the seed filling stage. Moisture stress imposed upon four forage legumes, berseem clover (*Trifolium alexandrium* L.), crimson clover (*T. incarnatum* L.), Persian clover (*T. resupinatum* L.) and squarrosum clover *(T. squarrosum* L.), reduced yield and yield components but had no effect on germination, germination rate index, seedling growth rate, and accelerated aging test Iannucci et al. (1996). However, seedling dry weight was significantly reduced under moisture stress (Iannucci et al. 1996). Seed vigor in berseem clover, estimated as germination after the accelerated aging test, was also reduced when plants were exposed to water deficit during seed fill (Iannucci et al. 1996). Late-terminal drought stress imposed on barley plant after beginning of seed filling period had no effect on standard germination, but significantly reduced seed vigor of barley as estimated the germination after accelerated aging test (Samarah and Alqudah 2009).

Other researchers reported that drought stress during seed development had no effect on seed germination and vigor. Vieira et al. (1992) found that drought stress imposed at beginning seed stage (R_5) or full seed stage (R_6) had no effect on seed quality, as estimated by seed germination, accelerated aging, and cold tests, across four cultivars of determinant and indeterminant soybean cultivars and 3 years of study, except for a slight reduction in 3-day germination and electrical conductivity. They attributed the reduction in 3-day germination in some of the drought stress treatments to the occurrence of hard seeds. Drought stress had little effect on seed quality unless it was severe enough to produce shriveled, shrunken, and miss-shaped seed (Vieira et al. 1991; Vieira et al. 1992). The proportion of shriveled, small, undeveloped soybean seeds that developed under drought stress in a two-year study was small and could be removed by conditioning to improve the quality of the remaining seeds (Vieira et al. 1991, Vieira et al. 1992). In peanut, water deficit during seed development slightly lowered seed germination, but had no effect on seedling vigor (Ketring 1991).

Recently Samarah et al. (2009c) found that the germination and vigor of soybean as estimated by the germination after accelerated aging test affected soybean seed quality by increasing the proportion of small-sized category seed (consisted of shriveled, wrinkled, undeveloped, and misshaped seeds), which had lower germination than large seeds due to exposed to drought stress. These results were in consist with Vieira et al. (1991), who reported that drought stress reduced seed quality if the stress sever enough to produce small, shriveled, wrinkled, undeveloped, and misshaped seeds. However, Samarah et al. (2009c) also found that the medium seeds produced under drought stress had lower germination. Drought stress reduced seed quality not only by increasing the production of small and medium seeds, which had lower germination, but also by decreasing seed vigor (AA-germination) of large, full, round seeds from severe-stressed plants compared with gradually-stressed and well-watered plants.

6 Conclusion

Drought stress has a great impact on the reproductive development of crops and consequently on final seed yield. The degree of drought stress is clearly determining factor for pollination, seed set, yield and quality in all species, but the response of species to drought stress varies. The complexity of both crop reproduction and plant stress responses makes it difficult to construct a simple model of ways in which successful reproductive development and high yield can be achieved under drought stress. However, where the final yield is concerned, all breeding manipulation strategies/approaches used in crop improvement under drought stress have to focus finally on flowering and/or grain development. Breeding strategies to improve crops yield should be based on improved response of crops to drought stress especially during reproductive stage when the reproductive organs are developing. Increase level of ABA and insufficient energy sources such sugar, starch and carbohydrate under drought stress negatively affects crop pollination processes in several approaches. One of these approaches is blocking of pollen grain/ovary growth and development; increase number of pollen grain/ovary abortion and sterility. The second approach is by decreasing quality/quantity of nectar and decreasing flower attractiveness to pollinator. The strong correlation between success of pollination process and yield is clear by seed set percentage. Increase level of ABA leads to decrease seed set percentage under drought stress. Drought stress decreases seed yield by decreasing the current photosynthetic supply and inducing reproductive organ abortion during reproductive development. Clear effects of drought stress on yield and yield components are by decreasing fruit and seed number per plant and

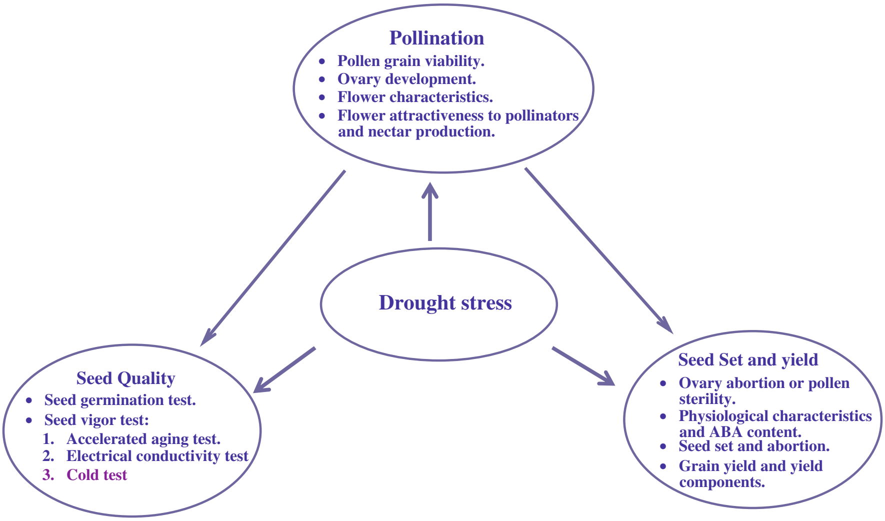

Fig. 3 Effects of drought stress on crops pollination, seed set, yield and seed quality

seed number per fruit, and decreasing seed individual weight. Seed quality is also another important trait affected by drought stress which decreases germination percentage and seed vigor (germination after accelerated aging test, cold test and electrical conductivity test of seed leachates). Understanding the correlation between pollination process, seed set, yield, yield components and seed quality can have a substantial influence on crop improvement, including the drought tolerance of reproductive processes, in the coming years. Also, it may be possible to prevent the irreversible effects of drought stress on the pollination, seed set, yield and seed quality (Fig. 3).

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Ecological Fertilization

György Füleky and Szilveszter Benedek

Abstract In the past decade it has repeatedly been shown that agriculture is a major source of environmental pollution. The environmental risk of industrial agriculture led to the concept of sustainable agriculture. Ecological fertilization integrates agricultural and environmental goals and is adjusted to the environmental conditions. Ecological fertilization is based on the principle that mineral fertilization should only be applied to the soil in the quantities and at the time required by the crop, thus avoiding damage to the environment. The present review provides a detailed description of the principles of ecological fertilization, such as accurate matching of nutrients to crop requirements, optimal condition in soil, favorable fertilizer use, and reducing nutrient losses. We review also practical systems such as integrated farming, site-specific fertilization, and organic farming. The most important legislations and regulations are also discussed.

Keywords Fertilizer • Nutrient • Soil • Environment • Integrated farming

1 Principle of Ecological Fertilization

In the past decade it has repeatedly been shown that agriculture is a significant source of environmental pollution. Rapid intensification of livestock production, a result of the focus on increasing productivity from the 1950s onwards,

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has contributed to a large increase in nutrient surpluses (Ramirez and Reheul 2009). The high levels of application of chemical fertilizers, due to the availability of these inputs at relatively low prices, has not only led to high and stable yields but also resulted in pollution of soil, water and air. Inefficient nutrient use and the concomitant nutrient enrichment of agro-ecosystems have contributed to agriculture's impact on aquatic systems (Mander and Forsberg 2000). Goossense and Meeuwissen (1990) concluded that nitrogen emissions to the environment in the form of nitrate leaching to the groundwater and volatilization of ammonia and nitrous oxides, mainly originated from animal manure both from excretions and application of slurry. Like excessive nitrogen fertilisation, this may lead to nitrate leaching. The NO_x-gaseous loss is also important by mineral fertilizers and is an assumed consequence of the intensive denitrification (Nótás et al. 2007). Conflicts between agricultural and environmental requirements with respect to phosphorus are discussed by Neeteson (1991) in view of recent evidence on the risk of P loss by erosion. Intensive arable farming is characterized by short rotations of high-return crops with high and stable yields. Inputs of fertilizers and pesticides strongly increased during the past decades. This made on one side the food production relatively stable, but on the other side also caused environmental problems. The high level of inputs is a consequence of aiming maximum crop yields, disease and pest free products and low labour requirements (Spiertz 1991).

The environmental risk of high intensive agriculture led to the concept of sustainable agriculture. Plant production and fertilization in sustainable agriculture have to be happen ecological correctly adapting to ecological parameters and avoiding environmental pollution, but also making sure the nutrient input to soil and so the food production (Lichtfouse et al. 2008). Sustainable agriculture implies successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources (Technical Advisory Committee 1989). Sustainable development is development, that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development 1987). Ecological fertilization integrates agricultural and environmental goals and is adjusted to the environmental conditions. Similar nutrient management principles are followed by organic farming, environmentally friendly fertilization and sustainable agriculture. Ecological fertilization is based on the principle that mineral fertilization should only be applied to the soil in the quantities and at the time required by the crop, thus avoiding damage to the environment, in contrast to organic farming, which is based on stricter principles and completely bans the use of mineral fertilizers. The present work provides a detailed description of the principles behind ecological nutrient management and the practical techniques for their implementation. Mention will also be made of legal regulations.

2 Realization of the Principle

2.1 *Accurate Matching of Nutrients to Crop Requirements*

This requires that the environmental conditions (soil, temperature, rainfall, etc.) should be correctly assessed as a basis for the choice of variety and the planning of yield levels. The same is true of precision crop production or site-specific mineral fertilization, but at a higher technical level. The latter requires a precise knowledge of soil heterogeneity and its causes, which can only be achieved using geostatistics to evaluate the sampling sites. The critical level concept (Fig. 1) may be in principle a valuable standard for diagnosis of the nutritional status of crops (Ulrich and Hills 1967). For many crops critical levels have been proposed for different plant parts. Adriano (2001) gives a comprehensive overview of these levels. The fertilization level applied to the plant stand must be chosen so as to prevent both nutrient deficiencies and luxury uptake, as excessive nutrient supplies may cause damage in several ways, leading to toxicity in the crop and leaching from the soil, while also being uneconomical. An alternative

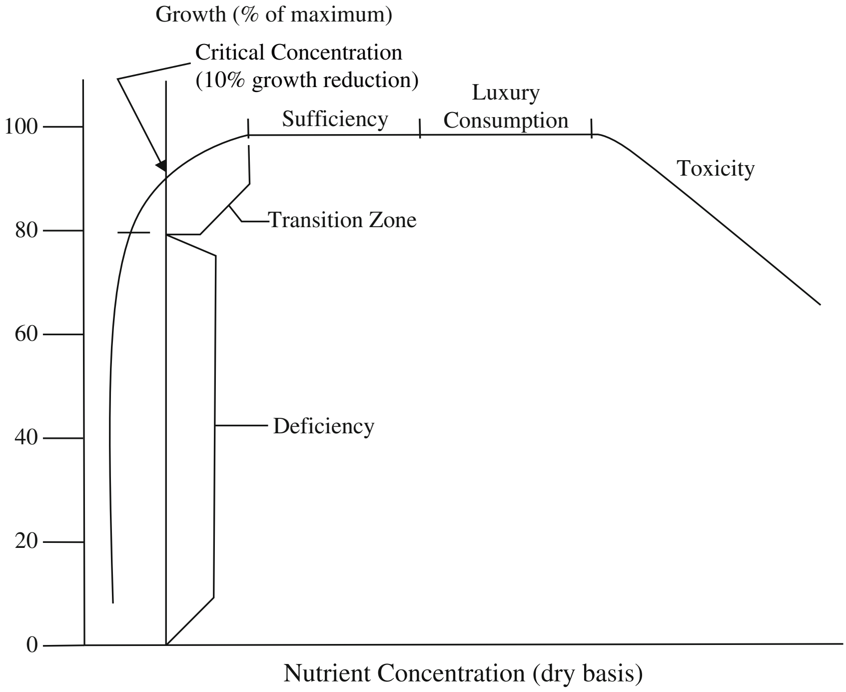

Fig. 1 Schematic view of the relationship between percentage of maximum growth and nutrient concentration of specific plant parts sampled at a given stage of development (Smith 1962)

approach to crop N management is to place more emphasis on the physiology of the crop during its growing season, aiming at a crop canopy that will intercept the maximum amount of light. This approach would place less emphasis on final yield or N uptake as the objective in seeking to estimate the amount of fertilizer N to be applied.

2.2 *Optimal Conditions in Soil*

2.2.1 Accurate Determination of Soil Nutrient Supply

Soil testing is a useful tool for nutrient management, as it provides an accurate gauge of nutrient levels in the soil and enables farmers to match nutrient application to crop needs. The greater the frequency of soil testing, the greater the likelihood that application rates match crop needs, hence soil tests at least once every three years may avoid over or under fertilization. This is an indicator of interest and awareness, even if recommended fertilizer application rates are not always followed (Paris and Reille 1999).

Now that reserves of P and K being built-up on many soils, the question can be asked, "To what extent should these reserves be accumulated and how can the reserves be maintained?" The Olsen P and exchangeable K at which yield approaches closely to the asymptote, can be considered the critical value. Below the critical value the loss of yield is a financial loss to the farmer. Above the critical value, there is no justification to further increase the available P and K because this is an unnecessary expense, and for P there is a risk of loss to water leading to the unacceptable consequences of eutrophization. From the concept of critical values and maintaining soils at these levels, there has developed advice to replace P and K removed in the harvested crop, i.e. maintenance or replacement fertilization. There is relatively little data on the length of time it takes for readily available P and K levels to decline under normal farming systems when P and K is not applied. The rate of decline will depend on the initial value, the amount of nutrient removed in the harvested crop, the size of the less readily available pool and the rate of transfer of nutrient from this to the readily available pool. In addition to exploiting nutrient reserves in subsoil, greater attention to soil cultivation and improved soil structure will allow plant roots to explore a larger volume of soil for nutrient acquisition (Johnston et al. 2001).

Measurements of mineral N in soil (N_{min}) have been used for several decades in some countries of continental Europe to guide advice to farmers on the quantity or timing of N fertilizer to be applied to a crop. Mineralization of organic N in soil is a key process in determining the quantity of N available to a crop, and hence the quantity of inorganic fertilizer required. The various factors which enhance or deplete the soil mineral N pool are summarized by Hofman and Cleemput et al. (1992): mineralization, rainfall, fertilizers, nitrogen fixation, immobilization, volatilization, denitrification, leaching, runoff erosion, plant uptake.

2.2.2 Consideration of Subsoil Nutrient Content

Malhi et al. (2009) found, that cropping systems that employed some form of fallow or green manure partial-fallow tend to accumulate more nitrate-N in the rooting zone (0–90 cm) than systems that are continuously cropped. Similarly, application of fertilizer N in excess of crop needs as occurred with the high input systems increased nitrate-N in the rooting profile, and contributed to leaching into the subsoil. Estimating the plant available nitrogen, the N_{min} method is used, which is measuring the ammonium and nitrate content of soil until 90 cm depth. The calculation of N fertilizer application rate has to be based on these data (Wehrmann and Scharpf 1979, Wiesler and Horst 1994).

Nitrate analysis show that there was only a few kg of nitrate-N in some horizons of the 3 m profile on control areas. As the N fertilizer rates rose, there was a rapid increase in the quantity of nitrate-N detected in the soil. The maximum nitrate accumulation was recorded at a depth of around 2 m in all cases, while the nitrate distribution curve also showed a minimum, generally at a depth of 40–80 cm. Nitrogen uptake by the roots had a perceptible effect on nitrate migration up to a depth of around 100 cm. At lower depths the majority of the nitrate is no longer available to the crop, so its further fate depends primarily on the downward movement of excess water. A considerable rate of nitrate accumulation can also be expected in soil horizons below 3 m at N rates of 180 kg ha^{-1} or more (Fig. 2) (Füleky and Debreczeni 1991; Füleky 1999).

In response to higher rates of mineral fertilizer the P content increased not only in the ploughed layer, but also in the 20–40 cm layer, and to some extent even at a depth of 40–60 cm. As the P balance became more positive there was a steep rise in the soluble P content of the 0–20 cm layer. The increase was less steep in the 20–40 cm, but the effect of mineral fertilization on the P content was still perceptible

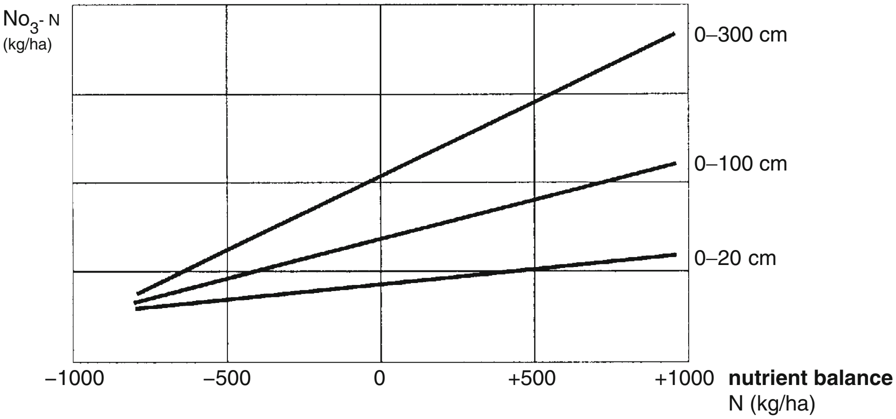

Fig. 2 Relation between N-balance and nitrate-N content of soil (Füleky 1999)

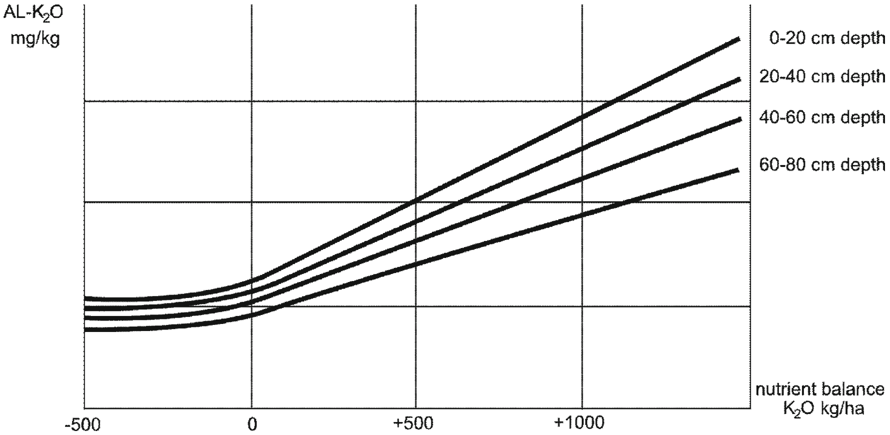

Fig. 3 Relation between K-balance and easily soluble K-content of soil (Füleky 1999)

in the 40–60 cm layer. At greater depths mineral fertilization had no detectable effect on the readily available P content of the soil (Füleky and Debreczeni 1991; Füleky 1999).

Rising rates of K mineral fertilizer caused a steep increase in the AL-soluble K content of certain soil layers. The effect of potassium fertilization, unlike that of phosphorus, could still be detected in the 60–80 cm soil layer (Fig. 3) (Füleky and Debreczeni 1991; Füleky 1999). The correlation between the nutrient balance calculated for a given field and the results of soil analysis is not sufficiently exploited in fertilizer recommendations. The results of long-term field experiments prove that the quantity of both less (phosphorus, potassium) and more (nitrogen) mobile nutrients accumulated in the soil, as detected by soil analysis, is in close correlation with calculated nutrient balances. In the case of more mobile elements, calculations must be made not only for the ploughed layer, but also for deeper horizons, and the nutrient contents of deeper soil layers must be taken into consideration when determining the mineral fertilizer rate. The curve shown in the figure can be used to predict not only the rate of nutrient accumulation, but also the extent of soil exhaustion. In general the P and K balances remain in the linear range for 20–30 years, only reaching a plateau and tending towards a constant soil analytical value after a long period of exhaustion

2.2.3 Maintain Optimal pH

It is now generally accepted that in much of Europe where liming materials are generally available, that the pH of arable soils should be maintained at pH 6.5 and that of productive grassland at pH 6.0 in water.

Russell (1973) discussing in detail the effect of soil acidity and alkalinity on plant growth, concluded that the effects of acidity over the normal pH range in temperate agricultural soils are due, not to the direct effects of the hydrogen ion concentration in the soil or soil solution, but to secondary causes. Principal among these is the effect of soil pH on the concentration of Al, Mn and Fe in soil solutions. A large Al concentration is the most common cause of the failure of agricultural crops grown on acid soils. Having established the soil pH values below which crop growth may be restricted on mineral soils and the effects of changes in pH on crop yields, most recent research effort has concentrated on determining the rates of loss of $CaCO_3$ from soils. Little Ca is lost in the harvested parts of arable crops. Most of the loss of Ca from agricultural soils is as a balancing cation for anions, nitrate, sulphate, chloride, bicarbonate, lost in water draining through the soil profile. This Ca must be replaced (Johnston et al. 2001).

Fertilizers, particularly if they are applied in large quantities for a long period, may cause unfavourable changes in the soil. Even without the application of fertilizers, intensive crop production may gradually acidify the soil as the result of root respiration. This is clear from the changes in the control plot in Fig. 4. This is aggravated nowadays by the substantial rate of acid deposition. Fertilizers, especially those containing NH_4^+, may also contribute to soil acidification. The drop in pH can be prevented by regular or occasional liming. This pH-reducing effect of mineral fertilization can be attributed to the migration of Ca and Mg ions away from the ploughed layer (Fig. 5). Parallel with acidification, there may also be a rise in the quantity of soluble toxic microelements in the soil (Stefanovits et al. 1999).

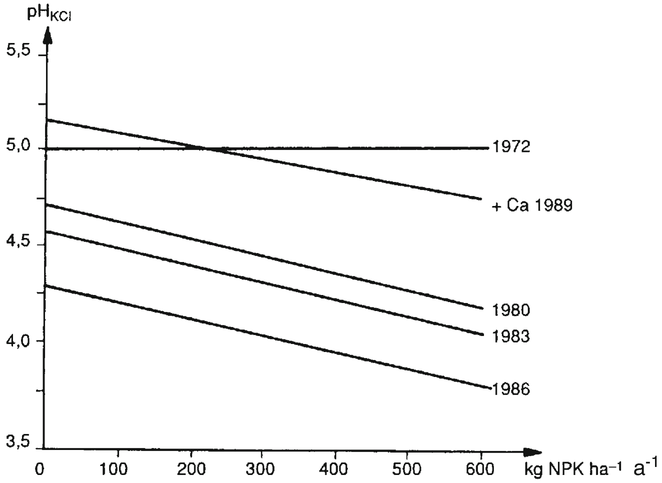

Fig. 4 Acidifying effect of environmental factors and mineral fertilization between 1972 and 1989 (Stefanovits et al. 1999)

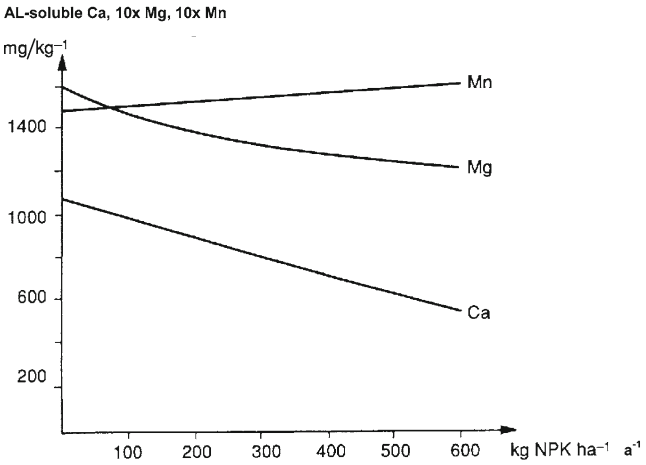

Fig. 5 AL-soluble Ca, Mg and Mn contents of the soil after 14 years of mineral fertilization (Stefanovits et al. 1999)

2.2.4 Increasing Organic Matter

It is very important to know the dynamics of soil organic matter. If the soil organic matter decomposes it provides mineral nitrogen and mineral phosphate, which - assuming K is adequate - might be sufficient for the crop. A major aim of organic farming is to build up organic matter in the soil for this purpose, by return of all organic wastes and by restorative crops. However, if this mechanisms is used to supply nutrient to a crop it implies that a pro rate amount of organic matter must be lost, the carbon being converted to CO_2. This loss can only be accepted to a limited extent, on grounds of general soil physical properties such as soil structure, water-holding capacity and erosion resistance. In any case, the decomposition of soil organic matter can provide only a limited amount of mineral N and P in any one year, because soil organic matter decomposition is controlled by the weather and the soil organic matter level, and cannot be manipulated closely (Tinker 2001).

The soil organic nitrogen was being build up by heavy manure additions, but as soon as these ceased in 1871, soil organic nitrogen declined as it was mineralized. It is impressive to see how long the manure effect can continue, with a greater rate of release than in the original soil, but as the rate of release declines, so will the crop yield. From the slope of the line, it seems that initially approximately 1 t N ha^{-1} was released in 40 years, or 25 kg N ha^{-1} a^{-1} (Fig. 6).

2.2.5 Mobilization of Nutrient Stock

Soils are inoculated with bacteria which apparently increase the plant availability of native and applied soil phosphorus. Several species of microorganisms are

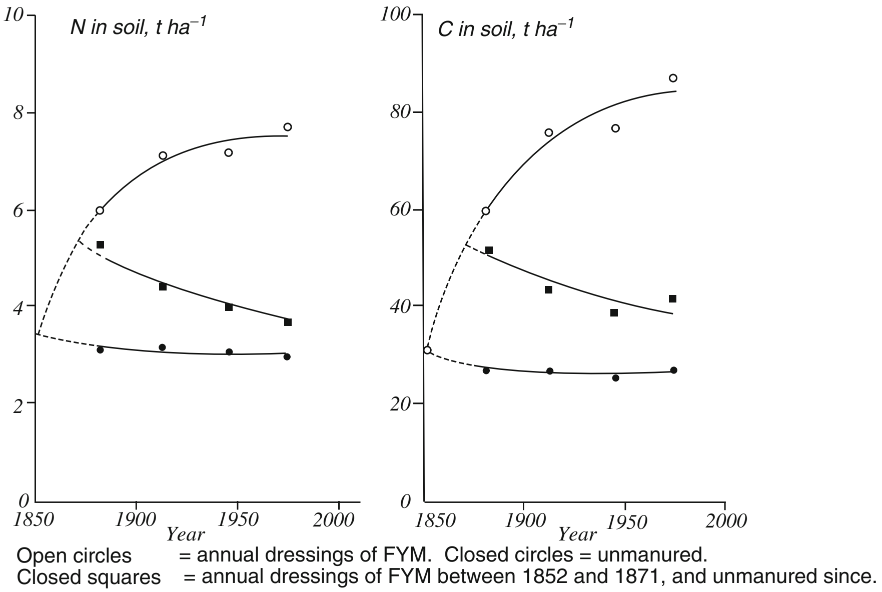

Fig. 6 Soil organic nitrogen and organic matter changes in topsoil receiving different manuring treatments (Johnston et al 1986) FYM: farmyard manure

effective in this respect, but the one principally employed is *Bacillus megatherium* var. *phosphaticum*. The increase in available soil phosphorus results primarily from the decomposition of organic phosphorus compounds. The treatment is most effective on neutral to somewhat alkaline soils and on those high in organic matter (Tisdale et al. 1985). Coherently, various “bio-fertilizers” for a high P-acquisition are increasingly offered worldwide. Many bio-fertilizers contain phosphate-solubilizing bacteria like *Bacillus* and *Pseudomonas* spp. for an improved chemical P-availability or phytohormone active algae extracts to stimulate root development for a better spatial P-acquisition (Bákonyi et al. 2008).

2.3 *Favourable Fertilizer Use*

2.3.1 Critical Value Concept

In the past, when the land was regularly used to grow crops without mineral fertilizer or sufficient organic manure, the nutrient balance was constantly negative and the natural nutrient-supplying capacity of the soil was exhausted (exhaustive nutrient management). Nutrient management aimed at soil fertility replenishment on soils with poor or very poor supplies of phosphorus and potassium involves a single high dose of mineral fertilizer or the regular application of fertilizer rates somewhat higher than the quantity extracted by the crop, in

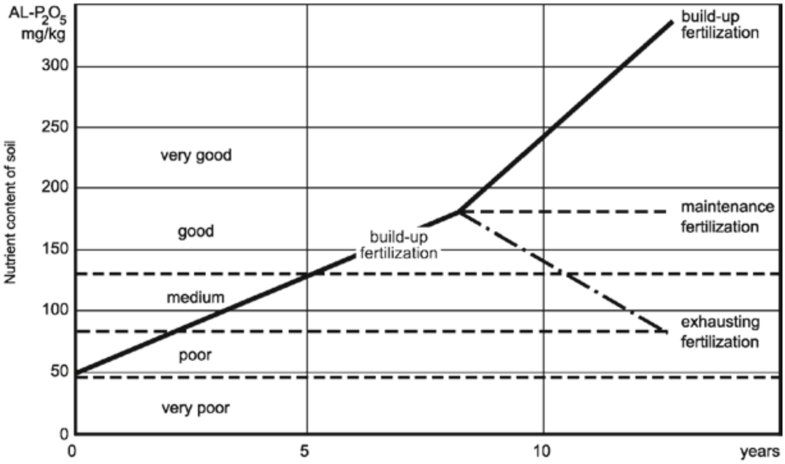

Fig. 7 Build-up, maintenance and exhausting fertilization (Füleky 1999)

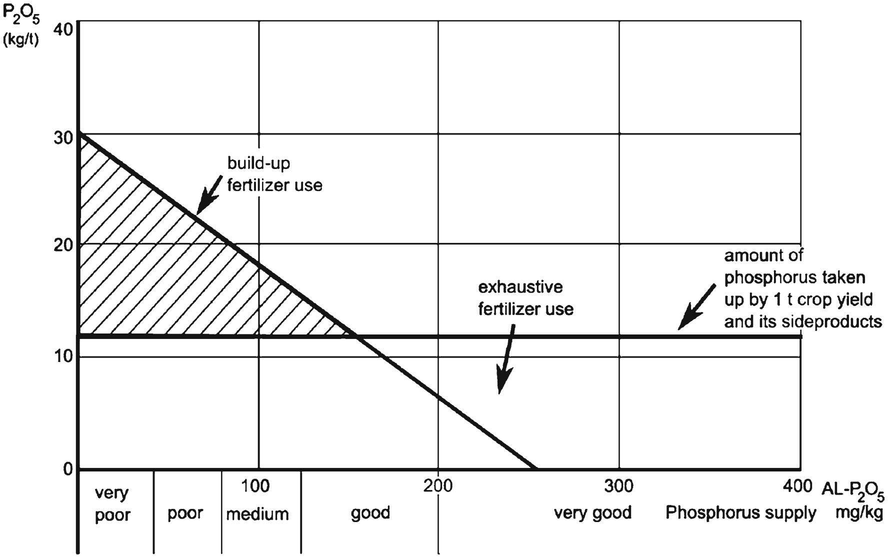

Fig. 8 Quantity of phosphorus fertiliser active agents recommended for a 1-ton yield of winter wheat on brown forest soil, as a function of soil phosphorus supplies (Füleky 1999)

order to bring the fertility level into the medium, good or very good category. After the medium, good or possibly very good category has been reached, nutrient rates that ensure fertility maintenance are sufficient, as further replenishment would be both uneconomical and environmentally dangerous (Figs. 7 and 8) (Füleky 1999).

Past research on phosphate has emphasized the need to maintain the plant-available concentration of P in soil above a critical value to ensure that crop yield is nit limited by a lack of P (Johnston et al. 1986; Johnston and Poulton 1992). For many crops and soil typed $NaHCO_3$-extractable P (Olsen-P) of 20–30 $mgkg^{-1}$ appears to be a critical value below which crop yield decline even if other nutrients are in plentiful supply. Concentrations in surface water as low as 20 μg Pl^{-1} can cause algal growth and eutrophication under some circumstances. In the Broadbalk Experiment the soil Olsen *P* value above which P movement became serious was about 60 $mg\,kg^{-1}$ (Heckrath et al. 1995).

From the concept of critical values and maintaining soils at these levels, there has developed advice to replace P and K removed in the harvested crop, i.e. maintenance or replacement fertilization. There is relatively little data on the length of time it takes for readily available P and K levels to decline under normal farming systems when P and K is not applied. The perception that on arable soils there had been a build-up of P reserves, together with known differences in the responsiveness of crops to P and K fertilizers, was reflected in the rationing of P and K fertilizers. With the introduction of cultivars with increasing yield potential and agrochemicals to control weeds, pests and diseases, farmers justifiably began to use more N together with P and K fertilizers. The effects of this increase in fertilizer use are reflected in results indicate that most of soils growing arable crops now have good reserves of P and K (Johnston et al. 2001).

2.3.2 Calculation of Nutrient Balance

A means of obtaining initial information on the fate of a nutrient within an agricultural system is to construct a budget, taking account of as many inputs and outputs as possible and of changes in its stock within the soil. Long-term experiments are a valuable resource for calculating nutrient budgets to provide an indication of the likely losses under a range of managements. In addition to monitoring inputs and outputs of nutrients, long-term experiments provide the possibility of detecting and quantifying slow trends in the stock of a nutrient within the soil: this cannot be done in experiments lasting only a few years (Füleky and Debreczeni 1991; Powlson 1997). Sylvester-Bradley et al. (1987) compared the estimated N inputs to and outputs from the winter wheat crop in England and Wales for the period 1974 to 1986. This showed that, until about 1980, the average input of N in fertilizer roughly equaled offtake in the crop. After this fertilizer inputs increased more rapidly than offtake, with input exceeding offtake by about 30 $kg\,N\,ha^{-1}\,a^{-1}$ during the 1980s. Another form of nutrient budget can be calculated for an individual farm. Watson and Stockdale (1997) describe a Whole Farm Nutrient Budget system in which as many internal flows within the farm as possible are measured or estimated in addition to movements to and from the farm. To be able to optimize the nitrogenous fertilizer rate applied to agricultural crops, the soil's available N must be known, particularly that provided by the organic matter's N mineralization. The methodology proposed to achieve this aim is based on determining the soil's mineral

N balance (Sanchez et al. 1998). Velasco et al. (2008) reports that the annual N balance in integrated agricultural systems is positive due mainly to concentrate feed inputs.

Öborn et al. (2003) introduces seven basic requirements for an appropriate use of element balances: Define the user and purpose: what is the objective of the element balances, what is the required accuracy and what is the proper methodology. Description of the system, its surroundings and the elements to be considered: what are the boundaries of the system, is the system homogeneous, are there subsystems and what kind of element species are involve. Description of the methodology and data acquisition strategy: which type of balance is being used, what are the data sources and what is the method and frequency of data collection. Description of the state of the (sub)system(s), e.g. in terms of depletion or enrichment. Description of the inputs of the (sub)system(s) over well-defined periods. Description of the outputs of the (sub)system(s) over well-defined periods. Check for consistency, completeness and correctness of the element balance by internal and external peer reviews.

2.3.3 Nutrient Management Plan

Nutrient management plans include requirements for the: Application of nutrients, including the rate and uniformity of spreading, of both chemical fertilizer and livestock manure, to restrict nutrient losses to water to an acceptable level. Maintenance of a minimum quantity of vegetative cover during (rainy) periods that will take up the nitrogen from the soil that would otherwise cause nitrate pollution of water. Establishment of fertilizer plans on a farm-by farm basis and the keeping of records on fertilizer use. Prevention of water pollution from run-off and the downward water movement beyond the reach of crop roots in irrigation systems.

In addition, nutrient management plans include land management elements, such as the use of crop rotation systems and the proportion of the land area devoted to permanent crops relative to annual tillage crops. The method of calculation for the use and frequency of soil tests is expressed as the promotion of farms conducting soil tests at different frequencies. A nutrient farm management plan is an indicator of farmer awareness of environmental issues, but nutrient plans are also introduced because of legislation (e.g. the European Union Nitrate Directive).

Nutrient management plans normally include restrictions on the: periods when the application of fertilizer is inappropriate; application of fertilizer to steeply sloping ground; fertilizer application to ground water saturated, flooded, frozen or snow-covered; conditions for application of fertilizer near water courses and capacity and construction of storage containers for livestock manure, including measures to prevent water pollution by run-off and seepage into the groundwater of liquids containing livestock manure and effluents from stored plant materials such as silage.

2.3.4 Using Crop Models

Systems, based on dynamic models of N transformations, offer powerful means of exploring ways of minimizing N loss within farming systems.

If agriculture is to be economical in the long term, achieving maximum profits with high yield stability while avoiding damage to the environment, it is in the interests of farmers to employ a site-specific crop production technology elaborated for the given territory based on local environmental and economic conditions, and taking into consideration known yield-reducing factors. An extremely important aspect of this is to consider the climate, the soil and the (variable) potential of the given crop when planning nutrient supplies, based on the desired yield (income) level. The following models can be applied in this planning process: Empirical models: At present the extension service generally makes fertiliser recommendations in the light of correlations based on the results of field experiments. These empirical or statistical models are constructed by determining the relationship between the yields obtained in experiments and certain measured variables. Dynamic yield simulation models: These are mechanistic models consisting of mathematical correlations that describe the processes determining the behaviour of the system, and are constructed by dissecting the system, quantifying the major processes and mechanisms, and rebuilding the system. In yield simulation models each process needs to be quantified in adequate detail in terms of both plant status (phenophase, leaf area size, nitrogen content, etc.) and the environmental factors influencing the process. The database required to run yield simulation models consists of four main fields: climatic and meteorological data, soil and relief data, vegetation, yield and production technology data, socio-economic data. Decision-making models: More and more frequently, yield simulation models are integrated with expert systems, allowing decision-making systems to be created, the demand for which is rapidly increasing in agriculture (Penning de Vries et al. 1989).

During the last 20 years there has been a strong move to provide information on a field-specific basis. Developments in the modeling of N cycle processes and the advent of computerized record keeping by farmers have facilitated this. A system being developed specifically for arable crops is SUNSDIAL: Simulation of Nitrogen Dynamics in Arable Land. Defining the N requirement of a crop, as required in all current decision support modeling systems, is not simple. In SUNDIAL the target N uptake of a crop is calculated from expected crop yield using empirically-derived parameters obtained from an analysis of field experiments with a range of arable crops. However, it is recognized that the link between, say, grain yield or total dry matter of a cereal and total N uptake is not direct; especially at higher values for N uptake there is considerable scatter. This is interpreted as an example of "luxury" uptake on N in which the crop absorbs additional N, if it is available, up to a maximum capacity during growth; this extra N does not necessarily lead to additional yield compared to a crop obtaining only just sufficient N (Powlson 1997).

2.3.5 Recycling Organic Materials

Long and short term soil improvement of manure and compost application are next: Improves soil structure. This improves water infiltration, mitigating against run-off which causes flooding and diffuse pollution, and also improves root penetration which increases crop yield. Improves water holding capacity through increased levels of organic matter. Makes the soil more drought resistant as organic matter can hold up to 20 times its weight in water. Increases levels of organic matter. In addition to improving structure and water holding capacity, soil organic matter increases the capacity of soils to bind chemicals, buffer the release of pollutants and regulate the supply of nutrients. It is lost from the soil through mineralization, erosion and land use change. Helps control soil erosion. Soil erosion has negative impacts on water quality and can lead to damaged habitats, sedimentation and loss of carbon. It can also have an economic impact on farmers (Sjöström 2008).

The nutrient content of organic manures must be taken into account when planning nutrient applications. Recycling to land and decomposition in the soil is the best practical environmental option in most circumstances for many organic materials as it effectively closes the carbon and nutrient cycles, returning the carbon, nitrogen, phosphorus and other nutrients to the soil they came from. Not everything in the material is good for the soil, nor for the environment: Some organic materials can include pollutants (for example metals, persistent organic pollutants, biocides and nanoparticles) that can accumulate in the soil to levels where they become toxic and can impair the long-term functioning of the soil. It is also important to stress the harmful substances do not only exist on organic manures, but also in other materials which are added to soil - for example in fertilizers. When proper attention is given to the composition of manures and decisions on rates, timing and application methods are made correspondingly, the nitrogen fertilizer replacement value of manure can be strongly enhanced. This should lead to a further reduction of mineral N fertilizer use, N surpluses and pollution (Schröder 2005).

To be able to optimize fertilizer plans and to maximize the utilization of nitrogen in manure, new techniques for application and new technologies for treatment have been introduced. Application of slurry with trailing hoses is recommended in winter cereal and injection is recommended on bare soil and grass. Broadcast spreading of slurries is prohibited. About one third of the total amount of slurry is injected (Birkmose 2009).

The recycling of plant nutrients in agriculture through the use of organic manures, biosolids and other organic wastes is discussed with special reference to phosphorus and its efficient use in crop production. The two end-products at sewage treatment works are the solid and the liquid. The liquid effluent contains water-soluble inorganic P and low-molecular weight organic P and both are bioavailable. It is this fraction of P that created problems associated with eutrophication in rivers. Currently this P can be removed by adding salts of calcium, iron or aluminum. There are conflicting results about the availability of this precipitated P to plants. Iron and aluminum phosphates may age and with time the phosphate in these compounds may become less available for uptake by roots (Johston 2008).

Managing food waste successfully is a commercial opportunity as well as being environmentally virtuous. Anaerobic digestion (biofertilizer plants) and food waste disposers have been found to have nearly equivalent global warming potential and better than the alternatives such as landfill, incineration or centralized composting. Wastewater treatment can recover 95% of the P from urban wastewater and concentrate it into the sewage sludge that, after appropriate treatment, can be applied to land as nutrient-rich soil improver (biosolids) (Evans 2008).

Granstedt et al. (2008) defines Ecological Recycling Agriculture as an agriculture system based on local and renewable resources that integrate animal and crop production on each farm of farms in close proximity. As a result a large pail of the nutrient uptake in the fodder is effectively recycled.

2.4 Reducing Nutrient Losses

2.4.1 Reducing Nitrate Leaching by Cover Crops

Cover crops are legumes, cereals, or an appropriate mixture grown specifically to protect soil against erosion; ameliorate soil structure; enhance soil fertility; and suppress pests. Cover crops are not grown for harvest, but rather to fill gaps in either time or space when cash crops would leave the ground bare (Lal et al. 1991).

N supplies can only be reduced in the fall if growing plant material with high N requirements and a high input rate exist in the field at the same time (Fig. 9). To solve these problems, special cover crop mixtures were tested. These cover crops have a high N consumption rate at the same time when the uptake rate of corn plants is decreasing considerably (Estler 1991).

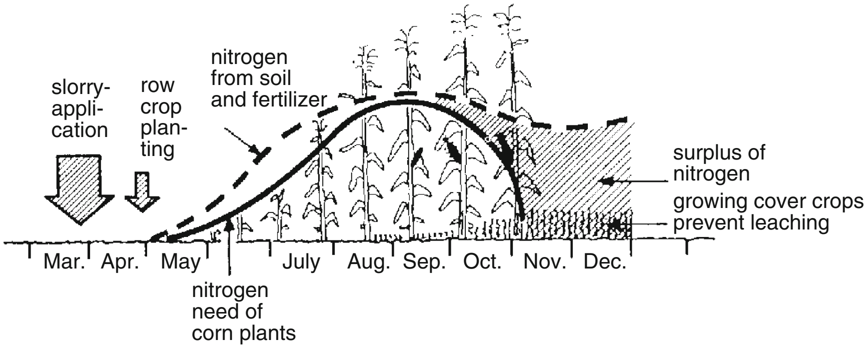

Fig. 9 Growing cover crops in the late fall can prevent leaching of surplus nitrogen (Estler 1991)

Almost 20 years ago it was demonstrated that the presence of an actively growing crop was an effective means of decreasing winter leaching (Widdowson et al. 1987). In one extreme case, over-winter loss appeared to decrease from well over 100 kg N ha^{-1} in the presence of late-sown winter wheat to about 30 kg N ha^{-1} where wheat was sown unusually early in September. Growing cover crop during winter is a method of decreasing leaching in the period when soil would otherwise be bare before sowing a spring crop. A more radical approach is to regard crop cover as an integral part of arable management and use an undersown cover crop even when the following crop is to be sown in autumn. It must be recognized that some crops and agricultural activities have greater environmental impacts than others. It will certainly be impossible to prevent all drainage or runoff water from every field from exceeding the EU 50 mg l^{-1} nitrate limit at all times. It is therefore necessary to consider water resources at the catchment and regional scale, recognizing that high nitrate water from some areas will be diluted by lower nitrate water from others. To some extent the modeling approach used for rotation planning, described above, can be used but there is also a need for policy makers to be able to conduct scenario testing using less detailed information for large areas of land. In a maritime climate any nitrate remaining in soil after harvest, plus that mineralized in autumn, is at considerable risk of being lost by leaching during the subsequent winter. From the standpoint of water quality it is therefore essential to aim at management practices that decrease the quantity of nitrate in soil in autumn. From agricultural standpoint it is also sensible to avoid unnecessary loss of a plant nutrient (Powlson 1997). Catch crop promotes the sustainability of agricultural systems by reducing soil erodibility and nutrient losses by nutrient uptake and transfer to the following main crops (Rinnofner et al. 2008). Doubling the catch crop area yielded a decrease in nitrate leaching (Decrem et al. 2007).

2.4.2 Crop Rotation

Crops differ greatly in the quantity of nitrate and readily mineralisable organic N left in soil after harvest and also in their ability to capture inorganic N left from the previous crop. Consequently a change in the sequence of crops grown in a rotation can have a significant effect on the quantity of nitrate leached during winter. to simulate N transformations in a large number of crop rotations that optimize N use and minimize loss (Smith and Glendining 1996). In areas of a field that, for some reason, regularly give higher crop yields, offtake of P, K and trace elements will be greater than in the rest of the field leading to a decline in soil reserves. It would then become necessary to replace these nutrients by increased applications applied selectively to these areas. It is well documented that ammonia losses from urea can be significant in warm dry climates but this is rarely the situation in spring in the UK and northwest Europe. Losses by denitrification (or leaching when it occurs in spring) may well be less from urea than from ammonium nitrate as the peak concentration of nitrate in soil is smaller. A possible strategy for minimizing losses of fertilizer N by leaching or denitrification is to apply part of the total dose to crop foliage instead of to the soil.

2.4.3 Buffering Strips

The low-lying areas of land that often lie between farmland and water courses can act as buffers by removing nutrients from the waters moving through them. Buffer strips remove nutrients by many postulated mechanisms, but two are clearly defined and dominant in nitrate removal: denitrification and nutrient uptake into plants growing in the strip. The uptake of nutrients by vegetation is important because it removes phosphate as well as nitrate and offers the facility to manage nutrient removal by managing the vegetation in the buffer strip. Grass is the most common form of vegetation although it may be possible to select other species that are more efficient. Wooded strips also exist and planted poplars have been suggested as good buffers (Haycoc and Pinay 1993; Correll 1997).

2.4.4 Expanded Fertilizer Margin

Where soil type and local hydrology are appropriate it may be possible to design an expanded field margin to act as a buffer zone to decrease nutrient movement to surface waters as described above. Even where this is not possible, having wider uncropped and unfertilized field margins may have a role in decreasing total nutrient loss from farmland to both surface-and ground waters. There is economic logic in regarding these areas as “set-aside” so that the crop is not sown in the edge areas, fertilizers and pesticides are not applied and grass or other plants are allowed to grow (Powlson 1997). Addiscott et al. (1991) suggested a surround of 15 m as a means of decreasing N-fertilizer use but with a proportionally smaller decrease in crop production.

2.4.5 Drainage Manipulation

A variation on the principle of buffer strips is the temporary restriction of flow in field drains where these have been installed in clay soils. This can be used to retain water in such soils early in the autumn/winter drainage season and is likely to have two important results. First, the cracks that develop in such soils during summer will close more quickly than normal, thus decreasing the extent to which a pulse of nitrate (and phosphate or autumn applied herbicide) moves through drains to surface waters by by-pass flow. Second, it is likely to create sub-soil conditions conducive to denitrification, thus decreasing the amount of nitrate at risk to leaching (Powlson 1997; Catt 1996).

2.4.6 Use of Slow-Release Fertilizers

The intensive use of N fertilizers in agriculture and horticulture together with nitrification inhibitors should be beneficial for the environment. However, to justify their higher price, these fertilizers must also offer economic advantages to the farmer to make them a viable alternative to conventional N fertilizers (Pasda et al. 2001; Carrasco-Martin 2008).The use of DMPP (3,4-dimetilhylpyrazole phosphate) nitrification inhibitors with urea reduced nitrate leaching. There were no differences in grain yield between treatments with and without DMPP at the same rate of N (Diez-Lopez et al. 2008).

2.4.7 Key Environmental Indicators

Key environmental indicators are widely used in financial accounting. Key environmental indicators are used more and more in relation to describing the conditions within crop production both concerning efficiency, sustainability and direct environmental effect. By doing this over a number of years is it possible to show the results of actions taken. Key environmental indicators elucidate actual changes that have been achieved on the farm. It is also possible to use environmental indicators as a basis for assessing and planning for future improvements (Törner and Drummond 1999). At present, key environmental indicators are used also for plant nutrient utilization and efficiency: N utilization (input/output), P utilization (input/output), P in circulation (recycled P/total input P), Balance (total surplus respective deficit), Crop production, Cattle, pigs/N losses, Housing, storage losses.

Figure 10 shows the flow of plant nutrients for the whole farm and each production area.

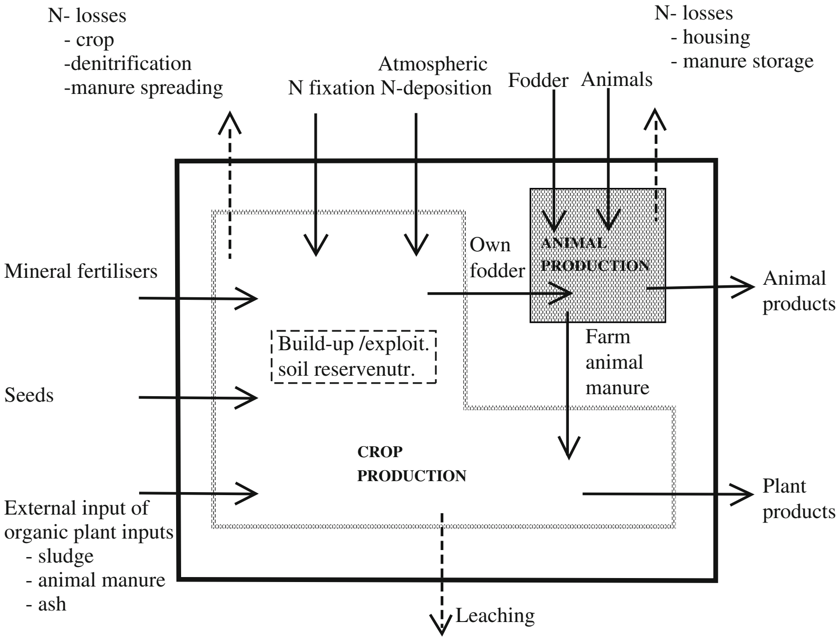

Fig. 10 The flow of plant nutrients (Törner and Drummond 1999)

Conservation in agriculture maintain the regenerative capacity of renewable resources; shift form the use of non-renewable to renewable resources and phase the use of non-renewable recourses. Maintaining the renewable resource base implies concern about the biological diversity of agro-ecosystems and the genetic diversity of crop and animal species. As has been pointed out already many agro-ecosystems rely upon suppression of biodiversity to favor the production process, but this is not incompatible with biodiversity within areas – for example the field margin or the hedgerow may be relatively undisturbed (Garret 2001).

3 Legislations, Regulations

3.1 Nitrate Directive

The purpose of Nitrate Directive (EU 1991) is protection of water bodies against pollution induced by nutrient from agricultural sources, and reducing the present nitrate pollution of water bodies. It is worth considering the subject of nitrate leaching. The amount of manure nitrogen leached following application to crop or land is principally related to the application rate and timing, the readily available-N content and the amount of rainfall following application. With pig manures, ammonium-N is rapidly converted in the soil to nitrate-N. Manure application during the autumn or early winter period should be avoided, as there is likely to be sufficient over-winter rainfall to leach a significant proportion of this nitrate before the crop is able to use it. Delaying applications until late winter or spring will reduce nitrate leaching and increase crop uptake and utilization of the nitrogen (Huxtable 2006). The basic options for nitrate remedial action are: closure of sources, blending with low nitrate water, treatment to remove nitrate (Croll 1994).

Whole farm manure N loading limit: Established a limit of 170 kg ha^{-1} of total N from livestock manures (deposited during grazing and by spreading) per calendar year, averaged across the farmed area. Closed period (organic manures): Prohibits the spreading of organic manures with high available nitrogen content during specified periods. The length of the closed periods ranges from 3 to 5 months, and it applies to all soil types. Manure storage: Requires farms to provide sufficient storage facilities to store all slurry produced by livestock during a period of 6 months for pigs and 5 months for cattle, and to store all poultry manure for a period of 6 months. Closed period (manufactured nitrogen fertilizers): Prohibits the spreading of manufactured nitrogen fertilizer during specified periods unless there is a crop nitrogen requirement. Crop nitrogen requirement limit: Requires farmers to plan their applications of nitrogen to crops and to comply with an upper cap on nitrogen applications (N max), assuming a set level of efficiency of nitrogen supply from any organic manure applications. Spreading locations: Requires farmers to undertake a written assessment to identify areas of land at risk of runoff and causing water pollution. Applications of nitrogen fertilizer and organic manures to areas of land identified as posing a high risk of runoff are prohibited. Spreading techniques: Prohibits the use of high trajectory application techniques for spreading slurry. Additionally, applications of organic manure to bare soil or stubble will require incorporation into the soil in certain situations.

Record-keeping: Establishes a requirement to keep a record of all N applications to land to facilitate compliance checking, and all to keep records of livestock numbers kept on the holding.

3.2 Waste Directive and Sewage Sludge Directive

The European Waste Directive (EU 2008) requires establishments and undertakings carrying out waste recovery or disposal activities. Compliance with the Quality Compost Protocol means that quality compost can be used on land without the need for waste management controls from the point at which it is dispatched to the customer This is provided that: the quality compost is produced using only source-segregated input materials listed in the Quality Protocol; the quality compost is destined for appropriate use in land restoration and soft landscape operations, horticulture and agriculture; the producer must obtain certification from the Composting Association; and the producer must keep copies of contracts of supply or information to customers which include a declaration of conformation with the Quality Protocol (Davis 2008).

The European Commission has indicated that it may review the Sewage Sludge Directive (EU 1986) to make sure that using sewage sludge for its nutrient content does not cause problems. The Sewage Sludge Directive aims to prevent harmful effects on soil, vegetation, animals and man and forms the basis for the regulation of sludge spreading in the EU. The metal content of sludge depends on the source and the inputs. Much work has been carried out to reduce the levels, and this is now having marked effects.

3.3 Good Agricultural Practice

Good Agricultural Practices of the FAO (2005) are a collection of principles to apply for on-farm production and post-production processes, resulting in safe and healthy food and non-food agricultural products, while taking into account economical, social and environmental sustainability. Good Agricultural Practices may be applied to a wide range of farming systems and at different scales. They are applied through sustainable agricultural methods, such as integrated pest management, integrated fertilizer management and conservation agriculture.

Good Agricultural Practices are related to soil in following points: reducing erosion by wind and water through hedging and ditching, application of fertilizers at appropriate moments and in adequate doses, i.e., when the plant needs the fertilizer, to avoid run-off (see nitrogen balance method), maintaining or restoring soil organic content, by manure application, use of grazing, crop rotation, reduce soil compaction issues by avoiding using heavy mechanical devices, maintain soil structure, by limiting heavy tillage practices, insitu greening manuring by growing pulse crops like cowpea, horse gram, sunhemp etc.

3.4 Soil Protection Strategy

Soil is a fundamental and ultimately finite resource. Although there are policy measures in place to protect our soils, many are still being degraded. Soil should also be seen as a non-renewable resource and needs to be utilized in a way that does not endanger it for future generations. The European Union adopted a Thematic Strategy for Soil Protection (EU 2006) aimed at raising awareness of potential threats and promoting an improved and more systematic response by Member States. The strategy focuses first of all on the low organic matter content of European soils. Consequences of SOM decline are: release of greenhouse gases, negative effects on biodiversity, including soil biodiversity, reduced water infiltration due to changes in soil structure, hence higher flood risk, reduced absorption of pollutants and increased water and air pollution, increased erosion. This has effects, such as: loss of fertile soil, loss of soil fertility, damage to infrastructures due to excessive sediment load, diffuse pollution of surface water, negative effects on aquatic ecosystems and thereby biodiversity, restrictions on land use and hindering future redevelopment and reducing the area of productive and valuable soil available for other activities: agricultural and forestry production, recreation, etc.

4 Practical Systems

4.1 Integrated Farming

Integrated farming optimizes multiple goals in nutrient management such as: maintenance of farm income and employment, protection of environment, landscape and valuable habitats, improvement of well-being and health of consumers by providing high-quality food, prevention of pollution and contamination (Spiertz and Zadoks 1989).

To develop systems for sustainable agriculture at the farm level, there is a need for a strategy of integrated nutrient management which fits in the integrated farming system. This strategy involves according to Vereijken (1991): soil fertility must be

Table 1 Description of the major fertilization variables in arable farming (Spiertz 1991)

	Farming system		
	Intensive	Integrated	Organic
Fertilization	Emphasis on mineral fertilization	Mainly organic	Excusive use of manure
P and K dressing	>withdrawal by crops	=withdrawal by crops	None
N dressing	Economic optimum	=withdrawal	None
Green manure	Grass	Grass-clover mixture	Grass-clover mixture
Organic manure	Only before potatoes	Frequently	Frequently, exclusively from own farm
Sugar-beet tops	Ploughed	Ploughed	Ploughed
Straw	Sold or ploughed	Ploughed	Using in loose to produce manure
Biodynamic preparations	None	None	Several

maintained at the appropriate level, not too low to attain stable yields and not too high to guarantee healthy crops with a low need of pesticides, dosage and application method of nutrients must lead to maximum utilization by the crops and to minimum emissions to the environment, chemical fertilizers should be substituted as much as possible by manure for the following reasons: to improve or at least maintain the physical, chemical and biological soil fertility, to balance of inputs and outputs of nutrients at the farm and regional level, especially in regions with intensive animal production resulting in less adverse effects on the environment and nature, to reduce costs and increase yield, to save non-renewable resources, especially energy for nitrogen fertilizer production.

The differences between nutrient management practices in intensive, integrated and bio farming are illustrated in Table 1. As pointed out by Csathó et al. (1998), sustainable nutrient management must concentrate on the fertilisation of the crop, rather than that of the soil.

Paris and Reille (1999) summarizes the JSR farm, as an example farm phosphate and potash fertilizer policy, which is normally based on: building up – applying more than crop removal in a low index situation; maintenance – replacement of nutrients removed by the crop and running Down – applying fewer nutrients than crop removal in a high index situation.

4.2 Site Specific Fertilization

Site-specific information technologies help to improve fertilizer efficiency and reduce negative environmental impacts (Torbett et al. 2008). To mitigate the ongoing consequences of soil deterioration, atmospheric CO_2 enrichment and NO_3^- pollution of ground and surface waters, N fertilization should be managed by site-specific assessment of soil N availability (Khan et al. 2007).

Precision farming is simply described as the adoption of the more precise management systems made possible by the use of modern technology. Essentially the technologies employed include the ability to provide an accurate location within the field, to make measurements within the field and potentially to be able to take actions variably within the field. Ideally such technologies should be largely automatic, since manual systems for location, measurement and action control are likely to introduce costs which could make the system uneconomic and unfeasible. It has been the recent automation of these components of the system which have made it potentially viable, even though there may have been an existing desire for more precise management, as illustrated by the efforts to apply lime variably according to manually measured variation of pH (Dawson 1996). The use of an N cycle model to give advice on fertilizer applications is based on the recognition that the N dynamics of different field vary. In fact there can also be significant variations within a field, often because of variations in soil type, drainage status, or the content of a nutrient other than N. The technology to vary fertilizer applications within a field in accordance with a predetermined map now exists, as does the facility for constructing yield maps from the output of a combine harvester.

Precision farming is thus not a new system of farming but is a more precise management opportunity, made possible by the development and adoption of new technologies. The methods (Figs. 11, 12, and 13) are as follow: soil sampling and analysis, mapping soil variables, assessment of the growing crop, nutrient offtakes by crops, mapping yields and offtakes, matching fertilizer applications and offtakes (Bryson 2005).

Having produced the yield map, it can be used as the basis of the fertilizer applications map, in which different rates of fertilizer are calculated for each yield band.

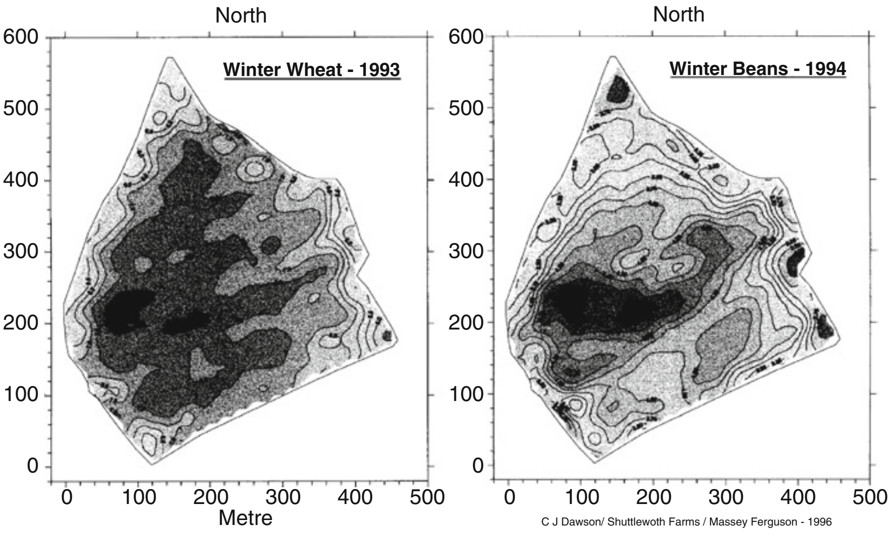

Fig. 11 Maps showing yield variation pattern two seasons (Dawson 1996)

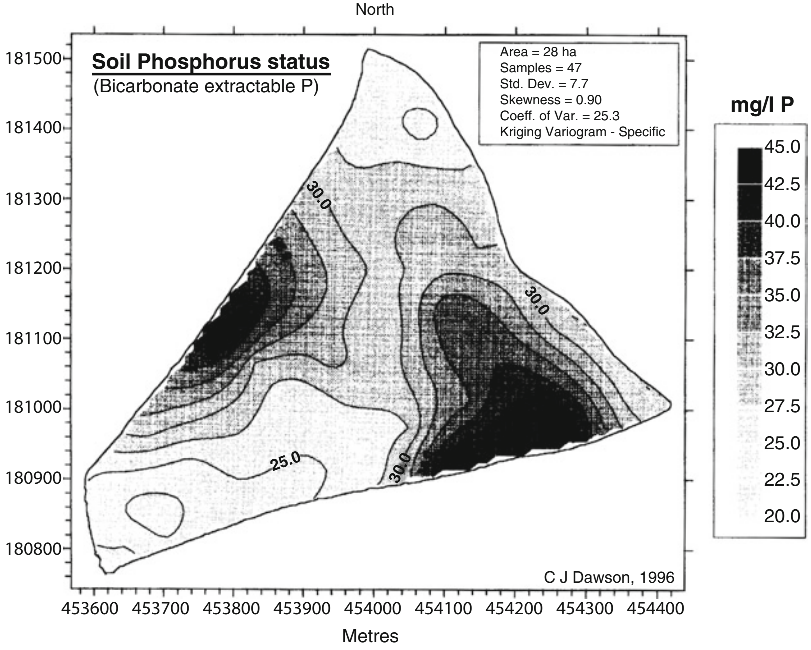

Fig. 12 Illustration of variation in satisfactory Olsen soil phosphorus values (Dawson 1996)

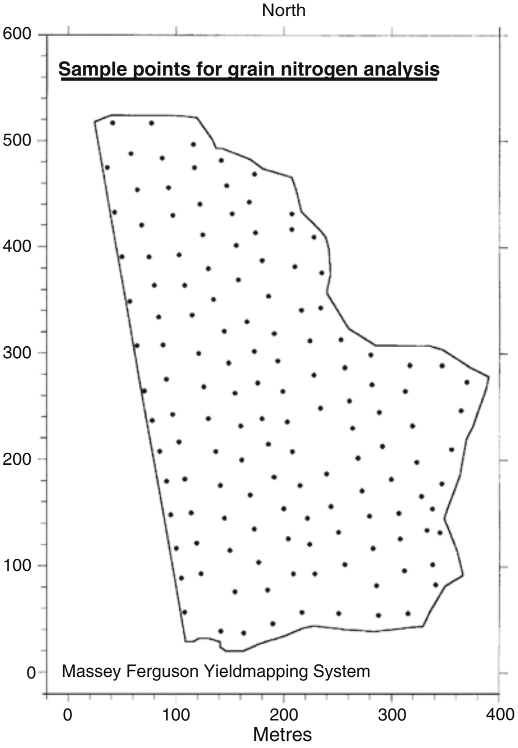

Fig. 13 Distribution of grain sampling points (Dawson 1996)

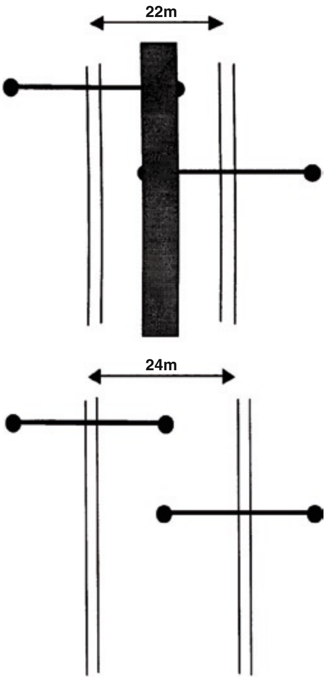

Fig. 14 Difference in the positioning of tramlines: correct tramline positions reduce the risk of spray over (Bryson 2005)

Figure 14 demonstrates the difference in the positioning of tramlines for a 24 m spray boom. Tramlines can be better positioned using a GPS system at minimal cost to the farm manager. Correct tramline positions reduce the risk of spray ove-lap. In addition to economic savings, improved product placement will help to reduce environmental pollution.

N-Sensor is a tractor-mounted tool that allows growers to measure a crop's nitrogen requirement as the tractor passes across the field and to vary the fertilizer application rate accordingly. The N-Sensor ensures that the right and optimal rate of nitrogen fertilizer is applied at each individual part of the field. It has become the benchmark technology for precision agriculture. N-Tester is a hand-held device that measures the nitrogen status of a crop from the chlorophyll content of its leaves.

4.3 Organic Farming

Organic farming results in the maximization of the use of natural resources by optimizing nutrient recycling in the soil-crop-animal system and omission of the use of pesticides and chemical fertilizers (Spiertz and Zadoks 1989).

Fundamental differences in principles in soil fertility and soil productivity management between conventional and organic farming can be identified for the following areas: Soil nutrient management, e.g. focus on fertilization of single crops vs. focus on nutrient management in crop rotations and at the farm level, dominance, dominance of single fertilization events versus. integrated nutrient management systems, highly soluble N and P fertilizers vs. prohibition of those fertilizers. Soil humus management: e.g. limited vs. optimized amounts, ranges and processing techniques of organic fertilizers and other organic matter input (Müller 2010).

5 Conclusion

In order to achieve ecological fertilization, the following data are required: The requirements of the crop to be cultivated and the dynamics of nutrient uptake, in order to determine the correct application date, method and quantity of fertiliser. From the practical point of view, it is important to know the critical range for each crop, to avoid environmentally dangerous over-fertilisation. If soil patches are to be given different rates of mineral fertiliser, it is essential to compile crop or yield maps. These are primarily used in precision nutrient management. The exact knowledge of the nutrient-supplying capacity of the soil also makes a decisive contribution to ecological fertilisation. The nutrient content must be determined not only in the ploughed layer, but also in the subsoil root zone, to ensure that these nutrient quantities (especially nitrate) are utilised by the crop and not leached into the groundwater. Continual efforts must be made to improve soil analysis methods in order to obtain an increasingly objective picture of the nutrient content available to the plants. Limit values or critical values, above which a substantial drop in the fertiliser effect can be expected, must be constantly reviewed to avoid applying unnecessary mineral fertiliser. Soil maps prepared using precise, geostatistical methods are also an efficient aid to nutrient management in precision crop production.

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Tropical Homegardens in Bangladesh: Characteristics and Sustainability

Mahbubul Alam

Abstract Homegardens are a species-rich and complex multistrata agroecosystem in the tropics. Those traditionally managed farming systems are of immense value in rural socioeconomy. The basic functions of tropical homegardens are generation of products for subsistence and earning cash income in areas with good market structure. Homegardens also provide a range of environmental services. In Bangladesh at least 20 million people maintain homegardens. Despite high social, ecological and economic functions, science of homegarden systems is not advanced. In this article I review the major advances in homegarden research. For that purpose I compared Bangladeshi homegardens with that of other tropical regions. Research findings on Bangladesh homegardens show that with a varying landholding size the homegardens differ in structure and composition across various agroecological regions of the country. Studies also report species richness from less than one hundred to more than four hundred occupying different strata. High socioeconomic performance, use of low external inputs, high dependency on household labor force and traditional – sometimes indigenous – management techniques are reported as some common characteristics in most homegardens of Bangladesh.

Keywords Biodiversity • Sustainability • Structural characteristics • Silvicultural treatments • Food security • Income security

1 Introduction

Homegardens are a characteristic feature of rural areas in many countries throughout all continents of the tropics. A general definition of tropical homegardens has been provided by Fernandes and Nair (1986) as a land use practice involving deliberate

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management of multipurpose trees and shrubs in intimate association with annual and perennial agricultural crops, and invariably, livestock, within the compounds of individual houses, the whole crop-tree-animal unit being intensively managed by family labor. Homegarden has been receiving increasing attention from scientists of various disciplines, especially agriculturists, ethnobotanists and human ecologists, because of its immense importance in conservation of plant genetic resources and social and economic roles played in rural landscapes of the tropics. Presence of abundant homegardens are reported from countries across the continents such as Nepal (Sunwar et al. 2006), India (Peyre et al. 2006), Sri Lanka (Hochegger 1998), Cuba (Wezel and Bender 2003)), Mexico (Blanckaert et al. 2004; Heriberto et al. 2008), Brazil (Albuquerque et al. 2005), Ethiopia (Abebe et al. 2006), Sudan (Gebauer 2005), Yemen (Ceccolini 2002), Tanzania (Soini 2005; Hemp 2006), Guatemala (Azurdia and Leiva 2004), Costa Rica (Zaldivar et al. 2002) and several regions of Indonesia (Abdoellah et al. 2006; Arifin et al. 1998). Locally homegardens are known in various names, e.g. *Kebun-Talun* and *Pekarangan* in Indonesia (Christanty et al. 1986), *Chagga homegardens* in Tanzania (Soini 2005), and *Shamba* in West Africa (Kumar and Nair 2004). Various other terms are also used by researchers to designate homegardens, for example kitchen garden (Brierley 1985), homestead forest (Rahman et al. 2005a), compound farms (Okafor and Fernandes 1987), homestead agroforestry (Leuschner and Khaleque 1987) and mixed garden horticulture (Terra 1954). In most available literature homegardens are reported to be predominantly a rural landuse system, although some recent studies indicated the presence of homegardening or conceptually similar farming systems in urban and peri-urban settings as well (Thaman et al. 2006; Drescher et al. 2006). Though homegardens are characteristic feature of the tropics, homegardens from temperate zone are also reported (e.g. Vogl and Vogl-Lukasser 2003; Gold and Hannover 1987). Nair and Kumar (2006) provided a comprehensive global distribution of homegardens, based on a selected 135 studies for the period 1990– 2003, in what they call ‘state-of-the-art in tropical homegardens’ book.

Homegardens are small-scale social-ecological systems embedded in larger social-ecological systems and managed through dynamic, constantly adapted traditional ecological knowledge largely embedded in local sociocultural and physical environment (Buchmann 2009). Even in the face of social and demographic changes in and around rural landscapes, homegardens itself remain relatively stable because of its diversification of accessible resources and such diversification serves as insuring roles against risks and disturbances (Abebe 2005; Kehlenbeck 2007). Until now the existing studies have provided a detailed account of homegardens in the tropics. ‘While some of them are at best scientific descriptions of a set of pattern (characteristics of systems at specific locations), some deal with examining homegardens in the context of current trends and issues in landuse systems, such as environmental integrity, carbon sequestration, biodiversity conservation, economic valuation of intangible benefits, and social equity, to name a few. Only very few of these are scientific analyses, however’ (Nair 2006).

As in many other tropical countries homegardens are age-old and traditional land use systems in Bangladesh maintained by at least 20 million people and land area covered by this farming system is 270,000 ha (GOB 1992) throughout rural areas. A homegarden in Bangladesh contains a house, a bare space, and a cultivated space. Usually the cultivated space (the garden) is located surrounding the house, in front of the house as front yard or behind the house as back yard. Douglas (1981) described homegardens of Bangladesh as a multi-storied vegetation of shrubs, bamboos, palms and trees surrounding homesteads that produce materials for a multitude of purposes, including fuel, shelter, structural materials, fruits and other foods, fodder, resins and medicines. Due to its social, economic, ecological and environmental benefits, homegardens are receiving progressively higher concentration by scientists, practitioners and policymakers. The Forest Policy of Bangladesh also recognized the importance of homegardens in rural livelihood. Despite such concerns research into this traditional farming system is not well advanced. There are only few in-depth studies conducted on various homegarden aspects. The purpose of this paper is to review existing literature especially on various structural and functional issues of homegardens in Bangladesh. It also attempts to compare Bangladeshi homegardens with that of other tropical regions in several aspects. The next section of this article provides an overview of the country's climate, prevailing landuse systems and a brief account of forest resources. The subsequent sections analyses homegarden typology, structural characteristics, species composition and biodiversity, socioeconomic contribution and application of indigenous knowledge in management. Building on these characteristics, sustainability of homegarden systems has been assessed towards the end.

2 Bangladesh: Country Overview

2.1 Location and Climate

Bangladesh is a country of Indian subcontinent situated in the tropics and almost surrounded by different provinces of India in the west, north, and east, in the southeast part, a small portion has boundary with Myanmar, and the Bay of Bengal encompasses the whole south. The absolute location of Bangladesh lies between 20°34′ and 26°38′ north latitudes and 88°01′ and 92°41′ east longitudes. The climate is greatly influenced by the presence of the Himalayan mountain range in the north, and Bay of Bengal in the south. Climatically, Bangladesh falls in tropical and subtropical zones, influenced mainly by latitude. The hill region, being comparatively of low altitude, does not exhibit well-marked altitudinal zone (GOB 1992). The mean annual rainfall varies from as low as 1,500 mm in the western region to as high as 5,000 mm in the northeast and eastern region. About 80% of the rainfalls in the country occur during monsoon. An average temperature during summer is around 28 °C, with a maximum of about 40 °C, while the temperature average during winter is around 18 °C, with a minimum of 7 °C. Although Bangladesh is predominantly a riverine country, droughts are not uncommon, and are seen to occur in a cycle of 5–10 years especially in the northern and northwestern part of the country.

2.2 Landuse Systems and Forest Resources

The total area of Bangladesh is approximately 14.40 million hectare (Mha), of which 12.46 Mha are land surface and 0.94 Mha are rivers and other inland water bodies. Among the landuse categories agriculture accounts for about 64% of the total land area and forest areas that include classified forest types, village woodlots, the rubber gardens and unclassified state forests (USF, under jurisdiction of district office instead of forest department) altogether accounts for 17.8% of the country's land area. Table 1 summarizes the land area of Bangladesh according to different landuse categories.

One of the peculiarities of the country's forest resources distribution of Bangladesh is that the resources are very eccentrically distributed (Rahman 2005). It will be a surprise to learn that 28 districts have no public forests at all (GOB 1992) and more than 90% of the government forests are concentrated within 12 districts in the east and southeastern region of the country. On the basis of geographical location, climate, topography and management principles, the forests of Bangladesh can broadly be classified into: Hill forests, Mangrove forests, Plain land *sal* forests (dominated by *Shorea robusta*, commonly known as *sal*), Unclassified state forests, Coastal forests and Homestead forests as shown in Table 1. Forestlands include 87% state forest (2.24 Mha) and 13% private forest (0.34 Mha). The state forest includes 67.86% classified forests (1.52 Mha) and 32.14% unclassified forests (0.72 Mha). Of the classified forests, 42.11% is hill forests (0.64 Mha), 7.89% is plain land Sal forests (0.12 Mha), and 50% is mangrove forests (0.76 Mha). On the other hand, of the private forests, 79.41% is homestead forests or homegardens comprising 0.27 Mha and rest 20.59% is rubber and tea gardens covering 0.07 Mha (GOB 1992).

Table 1 Summary of land area of Bangladesh by landuse categories

Landuse category	Total area (Mha)	%
Agriculture	9.25	64.2
Classified Forests	1.49	10.3
Unclassified State Forests	0.73	5.1
Village Woodlots[a]	0.27	1.9
Plantation Tea and Rubber	0.07	0.5
Housing and Settlements	1.16	8.1
Water Area	0.94	6.5
Other Uses	0.49	3.4
Total	14.40	100

Source: GOB (1992)

[a] includes fruit trees

3 Structure and Characteristics of Homegardens

Homegardens of the tropics exhibit remarkable variation in structure, species composition, area allocated for production and level of dependency on this farming system. The structural characteristics vary from region to region depending on local and regional physical environment, ecological characteristics, degree of commercialization, local socioeconomy and socio-cultural variations (Abdoellah 1990; Kumar and Nair 2004; Abdoellah et al. 2006). Owners' specific needs and preferences are additional determinants of the homegarden structural characteristics (Abdoellah et al. 2006). The following sections give an overview of structural characteristics of tropical homegardens with specific emphasis on Bangladesh (Fig. 1).

3.1 Size, Typology and Spatial Configuration of Homegardens

Homegarden size varies to an extent depending on total landholding size of the farmers, farmers' wealth status, and level of intensity of production, among other things. Average size of homegardens ranged from 0.05 ha to 0.16 ha with a mean of 0.08 ha in six districts of southwest Bangladesh (Kabir and Webb 2007). Homegarden size reported from other regions of Bangladesh include 0.04–0.43 ha in the off-shore island Swandip (Alam and Masum 2005), 0.05–0.21 ha in central region (Rahman et al. 2005a), 0.06–0.13 ha in northeastern region (Rahman et al. 2005b), and 0.02–0.25 ha with an average of 0.12 ha across various landholding size classes in northwestern Bangladesh (Alam 2008).

Fig. 1 An illustration of typical homegarden components in Bangladesh. The illustration shows arrangement of various homegarden components including the living quarter, cattle shed, vegetable garden and tree vegetation

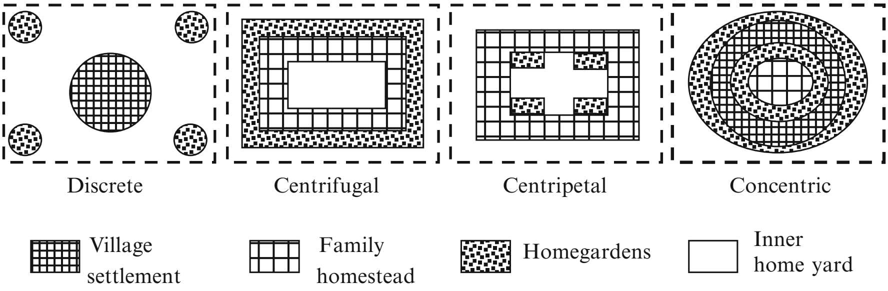

Fig. 2 Typology of homegardens according to their location in relation to rural settlement

Usually homegardens occupy the highest flood-free land adjacent to the homestead. Ali (2005) described four types of homegardens in terms of horizontal arrangements of their components: *discrete* type homegardens located on small mounds built separately about 200 m away from one another; *centrifugal* type, where homegardens occupy the outer courtyards extending upto 50 m from the living quarter; *centripetal* type, in that homegardens occupy the inner courtyard and are irrigated by household sources; and *concentric* type, where homegardens occupy lands adjacent to the homesteads upto 50 m as well as around the rural settlement upto 200 m away from the living quarter (see Fig. 2).

3.2 Vertical Stratification

Tropical homegardens create multistoried vegetation of different strata. Trees, shrubs, palms, herbs, climbers and ground vegetation can easily be identified in different layers (Fig. 3). Three to five layers are reported in different studies. The height of different strata varies to an extent depending on the species composition and regional climate and soil characteristics that determine tree growth. Different species are dominant in different strata. In the homegardens of Andamans, for example, top storey is occupied by areca nuts and with few forest species reaching upto a height of 16 m (Pandey et al. 2007). In contrast, 88.6% of the plant individuals of commercial crop, e.g. *Allium fistulosum, Ipomoea batatas, Brassica sinensis*, in Indonesian homegardens belong to ground storey (<1 m tall) (Abdoellah et al. 2006).

(Millat-e-Mustafa et al. 1996) summarized the vertical structure of homegardens of Bangladesh by stratifying individual plants into six strata and concluded that homegardens in general display consistent vertical structure throughout the country. On per hectare basis total number of individual plants across different regions varied from 1,189 to 2,462. However, densities of individual plants were much higher in the lower three strata, than in the other (Table 2).

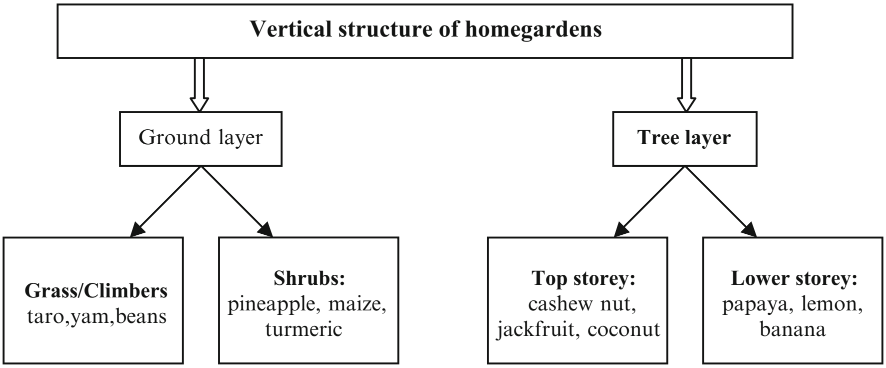

Fig. 3 Vertical structure of tropical homegardens showing various species components in different layers

Table 2 Vertical distribution of plants (range of values) in traditional homegardens in Bangladesh (Millat-e-Mustafa 1996)

Region	Total individuals ha^{-1}	Vertical strata					
		S_0[a]	S_1	S_2	S_3	S_4	S_5
Southwestern	1,909–2,462	424–704	368–693	337–719	158–265	38–225	17–136
Northwestern	1,189–2,078	139–614	325–742	86–230	52–225	150–426	81–128
Eastern	1,389–2,380	271–583	435–742	233–348	163–231	69–471	12–2,150
Central northern	1,754–2,314	325–478	377–793	337–756	91–323	145–231	35–355

[a] Number of individuals

4 Species Composition and Biodiversity

Irrespective of geographical areas, within the similar ecological region, the species present in the homegardens do not vary significantly (Nair 2006). Exception may occur in case of the species that are not common outside their limited geographical areas of distribution. However, the dominant species of tropical highlands will be different to those in tropical lowlands because of the variation in ecological characteristics. Such high species diversity has been a major driving force in sustaining the homegardens for centuries irrespective of geographical distribution. Nair (2006) summarizes commonly reported homegarden plants of the tropics (Table 3).

The limited number of studies has revealed high species diversity in the homegardens of Bangladesh. Millat-e-Mustafa et al. (1996) documented 92 different trees species in the traditional homegardens. Kabir and Webb (2007) documented 419 different species of trees, shrubs, herbs and climbers in the southwestern region. In the southwestern Bangladesh, where topography is coastal plain and soil is sandy and saline, the most important tree species available in the homegardens include *Cocos nucifera, Areca catechu, Psidium guajava* and *Spondias pinnata*. Shrubby species occurring with highest relative frequencies include *Citrus limon, Eupatorium*

Table 3 Commonly reported plants in homegardens of humid tropical lowlands (Nair 2006)

Category	Species in homegardens
Root and tuber crops	*Colocasia esculenta* (taro), *Dioscorea alata* (greater yam), *Dioscorea esculenta* (sweet yam), *Ipomoea batatas*(sweet potato), *Manihot esculenta*(cassava), *Xanthosoma spp.*(tannia or cocoyam)
Other food crops	*Ananas comosus*(pineapple), *Arachis hypogaea*(peanuts), *Cajanus cajan*(pigeon pea), *Passiflora edulis*(passion fruit), *Phaseolus*, *Psophocarpus* and *Vigna spp*. (beans and other legumes), *Saccharum officinarum* (sugarcane), *Zea mays* (corn=maize), and various vegetables
Fruit and nut yielding perennials	A*nacardium occidentale* (cahew nut), *Annona spp*. (soursop and sweetsop), *Averrhoa carambola* (carambola), *Artocarpus heterophyllus*(jackfruit), *A.altilis* (breadfruit), *Carcia papaya* (papaya), *Citrus spp.*(lemon,lime orange, tangerin), *Cocos nucifera* (coconut), *Ficus spp*. (edible figs), *Mangifera indica* (mango), *Musa spp*. (bananas and plantains), *Persea americana* (avocado), *Psidium guajava*(guava), *Spondias dulcis* (vi apple,hogplum), *Syzygium malaccense*(Malay apple), *Tamarindus indica*(tamarind)
Spices, Social beverages, and stimulants	*Areca catechu* (betel nut), *Cinnamomum zeylanicum* (cinnamon), *Curcuma longa* (turmeric), *Cymbopogon citrates* (lemon grass), *Piper betel* (betel vine), *Piper methysticum* (kava), *Zingiber officinale* (ginger)

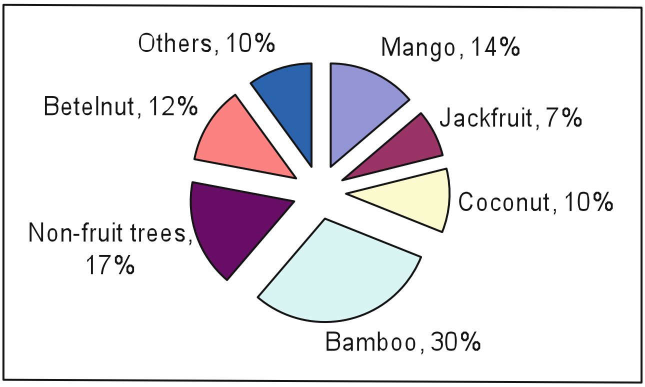

Fig. 4 Composition of various tree species in the homegardens of Bangladesh (GOB 1992)

odoratum and Clerodendrum inerme (Kabir and Webb 2007). The soils developed from *Madhupur clay* in central Bangladesh support a wide range of homegarden species including *Artocarpus heterophyllus, Mangifera indica, Cocos nucifera Tectona grandis, Anthocephalus chinensis* and *Litchi chinensis* (Rahman et al. 2005a). Tropical moist deciduous forest, commonly known as Sal (*Shorea robusta*) forest has also developed on the terraced soil of this region (Alam et al. 2008).

The statistics of Forestry Master Plan of Bangladesh (GOB 1992) indicate that mangos constitute highest percentage among the fruit species in the homegardens of the country. Non-fruit trees altogether constitute about 17% of the total plant individuals, and bamboos occur in highest abundance (30%) among the non-tree species (Fig. 4).

5 Management

The management of homegardens in Bangladesh is mostly traditional and sometimes indigenous in nature. Farmers manage their homegardens based on their generation-old experience that has passed on from their ancestors.Scientific management option, improved silvicultural practices and state-of-the-art knowledge base is inaccessible for them. Although the existing forest policy of the country recognizes the importance of homegardens, virtually no government intervention can be seen to improve overall system performance.

The farmers select species for planting based on its intended end use. Previous studies confirmed that rural people show special preference for fruit bearing species (Alam 2009; Rahman et al. 2005a; Alam and Masum 2005). A high preference for fruit species may be attributed to their multipurpose usage such as food, fodder, fuelwood and timber. For example, the main fruit species grown in the homegardens of Bangladesh are jackfruit and mango that contribute to the household by providing food, cash income, leaves as fodder and valuable timber (Rahman et al. 2005a).

The homegardens in Bangladesh are subject to light to moderate silvicultural treatments. Farmers manually carry out soil working and weeding, watering, mulching, and fencing for better survival and establishment of the plants, especially in the early stages of garden establishment. Of the tree level management, farmers carry out different cultural practices including thinning, pruning, and pollarding.Pruning is popular among the farm holders because a substantial amount of fuelwood can be collected besides inducing tree growth. In addition, sanitation pruning is done for some species like coconut and betel nut in the hope of reducing disease susceptibility. Dead branches and debris are also removed for the same reason. Light pollarding is done to induce flowering and fruiting of some horticultural species.

6 Socioeconomic Role

People have been cultivating a wide range of plants of various species and life forms in and around their living place for alternative source of forest products and environmental as well as cultural services since the time when they started plant domestication in the early stage of human history. The current form and composition of homegardens is an outcome of farmers' numerous practices of 'trial and error'.

Homegardens with their high species diversity are basically maintained for subsistence production throughout the rural tropics. A wide spectrum of multiple products including vegetables, fruits and spices are produced year round. Hence, the homegardens contribute towards food security (Fernandes and Nair 1986) and nutritional security (Nair 2006) of the rural poor (Fig. 5). Such multiple products are sometimes sold in the local market when those are in excess and when the farmers are in crisis for cash. The farmers become inspired of selling homegarden products in the regions with good market access (Abebe et al. 2006). Findings reported in literature from tropical countries indicate a wide range of contribution

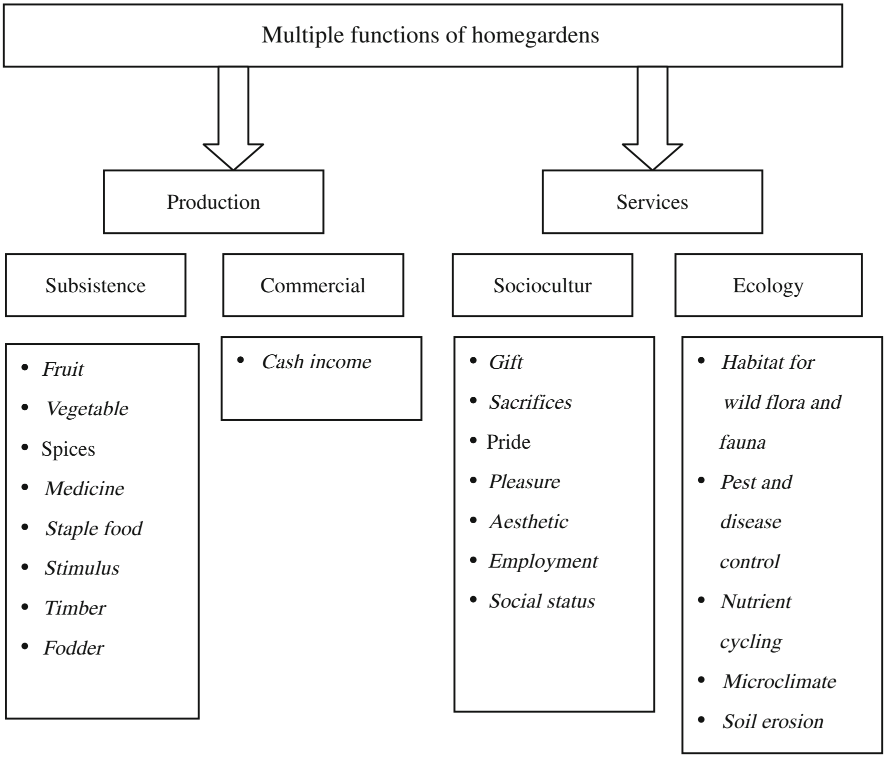

Fig. 5 Multiple production and service functions of the tropical homegardens (Kehlenbeck et al. 2007)

of houmegarden products to household economy; such contribution range from 0% (Méndez et al. 2001) to 50% (Trinh et al. 2003) of the annual family income.

Homegardens of Bangladesh supply 70% of timber and 90% of fuelwood and bamboo requirement in the country annually (Singh 2000). They are also a major source of forest products, and play an important role in the economic life by supplying the bulk of wood and other forest products in the local and regional market (GOB 1998).

The average annual value of gross production of homegardens in Bangladesh is US$228.2 per household (US$2670.9/ha), of which US$89.2 (39.1%) is used by the household and US$138.9 (60.9%) is sold. The overall contribution of income derived from homegarden products to average household income has been estimated to be 11.8% (Rahman et al. 2005a).

7 Marketing of Products

Marketing is one of the most important phases of any natural resource management system. Unfortunately, this phase in homegarden resources management failed to gain any attention form resource managers, policy makers, and even from academic

Fig. 6 Freshly harvested timber from homegardens, ready for transporting to sawmill

researchers. In refereed literature sources there exist almost no information regarding marketing of homegarden products in Bangladesh.

An explorative research revealed that the main market outlets for timber and timber products were sawmills located at local markets or nearby urban town, local fairs, and distant urban settlements (Rahman 2005). After buying the standing trees from the homestead owners, middlemen/suppliers employ labors to fell, process trees and gather them around nearby roads or riverbanks (Fig. 6). Axes and handsaws are used in felling, debranching, and sizing of the trees. Then middlemen channel down the logs to sawmill setup at nearby local market or urban places or to the wholesalers usually based in the same places. Middlemen usually use carts, human pulled-vans, and country boats to distribute the logs up to sawmills (see Fig. 7 that shows stacking of homegarden timber in the sawmills). Sometimes trucks are used depending on the volume of logs and distance of the sawmills. It was reported that price of timber varied according to species, quality, location of area, demand for the products, season and so on. In Table 4, it may be noticed that, in general, timber prices were highest in central region followed by those of northeastern and southern regions. The average producers' price was highest for teak (*Tectona grandis*) followed by mahogany, jackfruit (*Artocarpus heterophyllus*), blackberry (*Syzygium grande*), silkoroi (*Albizia procera*), rain tree (*Albizia saman*), kadam (*Anthocephalus chinensis*), and mango (*Mangifera indica*).

Fruits and vegetables in Bangladesh are grown for two purposes: subsistence and commercial. Subsistence-based production occurs mostly in the smallholders' homegardens, where as commercial production is the sole domain of the large landholders in their large homestead land as well as in special areas allocated for vegetables or fruit orchards. Vegetables grown in the homegardens are rarely sold in the market since those are produced on subsistence-based. The fruits after meeting the family demand are sold in the local market directly or through the middleman. Land area devoted for fruit growing in Bangladesh is

Fig. 7 Logs brought from nearby homegardens, ready for conversion in the sawmill

Table 4 Average sale and producer prices of main timber in different regions of Bangladesh

Forest products	Bagerhat area ($n=30$) (Southwest region)		Gazipur area ($n=30$) (Central region)		Sylhet area ($n=30$) (Northeast region)		All area ($n=90$)	
	Sale (cft)	Sale value (BDT)	Sale (cft)	Sale value (BDT)	Sale (cft)	Sale value (BDT)	Sale (cft)	Sale value (BDT)
Mango	5.3	650.0	5.0	830.0	3.2	489.0	4.5	656.3
Rain tree	6.7	1283.3	0.4	88.0	4.2	813.3	3.8	728.2
Jackfruit	1.8	563.3	6.7	2152.7	1.5	443.3	3.3	1053.1
Mahogany	6.3	1993.3	0.0	0.0	0.0	0.0	2.1	664.4
Kadam	0.0	0.0	0.0	0.0	2.8	410.0	0.9	136.7
Blackberry	0.0	0.0	1.3	313.3	0.7	176.7	0.6	163.3
Teak	1.0	413.3	0.7	333.3	0.0	0.0	0.6	248.9
Silkoroi	0.0	0.0	0.3	83.3	0.3	73.3	0.2	52.2
Others	2.8	553.3	0.3	58.7	0.0	0.0	1.0	204.0
Total	24.0	5456.7	14.6	3859.3	12.8	2405.7	17.1	3907.2

Source: (Rahman 2006)

BDT Bangladeshi Taka (1 US$ = 59.76 BDT in 2004), *cft* cubic feet (1 $m^3 = 35.2$ cft)

about 202,024 ha and about 80% of the total fruits are grown exclusively in the homegarden (Hossain 2004). An FAO survey (mentioned in Hossain 2004) shows that about 36% of retailers, 27% of traders and 22% of consumers buy fruits directly from the farmer who usually sell fruits in the weekly markets (locally called *hats*) and partly in the roadside and daily markets (locally called *bazaar*) (Fig. 8).

Fig. 8 Farmer carrying homegarden produced fruit (Jackfruit) to the local market

8 Sustainability of the System

8.1 Sustainability: Concept and Indicators

The term ‘sustainability’ has become a common keyword in most environmental and development analysis. The current-day concept of sustainability is the retrieval of the ancient wisdom dictating that ‘you don’t eat your seed corn’ (Nair 2006). Most often the terms sustainability or sustainable development are defined from the texts of Brundtland Report (WCED, 1987) as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” CGIAR (1988) defined sustainability of agricultural systems as the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving natural resources.

In most literature, sustainability of a system is described in terms of ecological and socioeconomic descriptors and indicators. While the ecological indicators include soil fertility, water availability, efficiency in the use of sunlight, nutrient cycling, and biodiversity of the systems (Huxley 1999; Torquebiau 1992; Kehlenbeck 2007), the socioeconomic indicators include labor requirement, resource inflows and outflows, and maintenance of food security and welfare (Abebe 2005; Torquebiau 1992; Conway 1985, 1987; Wiersum 1990).

8.2 Characteristics of Homegardens as Sustainable Agroforestry System

Based on the criteria, descriptors and indicators of sustainability, homegardes are designated as a sustainable agricultural system. Kumar and Nair (2006) mentioned tropical homegardens as ‘time-tested example of sustainable agroforestry’. Soemorowoto and

Conway (1992) designated 'sustainability' as one of the four sets of system properties of homegardens and 'because the homegarden is one of the world's oldest forms of agroecosystem, it must be regarded, at least in general terms, as highly sustainable'. The three factors that contribute to homegarden sustainability include its dependency on solar and human workforce; closed nutrient cycle together with reduced soil erosion; and high biodiversity at genetic level (Soemorowoto and Conway 1992). However, by saying that 'homegarden is a sustainable farming system' it should not assume that the structure and characteristics of homegardens are stable (Abebe et al. 2006; Kumar and Nair 2004). Like any other landuse system it is sensitive -and thus respond- to changes brought about by socioeconomic dynamics and market force.

Homegardens are multistrata systems resembling virgin tropical forest. Such multilayered vegetation structure with high species and genetic diversity ensures efficient utilization of resources (e.g. sunlight and soil nutrient), maintains soil quality, ensures efficient nutrient cycling, and ultimately conserves environment as a whole. Hence the multistrata forest-like system conserves and maintain resource base for future utilization and thus maintains sustainability of the system.

Homesteads in many countries, as in Bangladesh, are established on slightly raised land compared to adjacent level ground. Because of such characteristics, the homegardens remain flood free and are least vulnerable to many environmental disasters. Moreover, homestead land together with the homegarden is sold as last asset of the farmer.

Homegardens with a number of components such as fruits, vegetables, bamboos, spices and wood products ensures a year round production of a wide spectrum of products. Such variety of homegarden products ensures food security and nutritional security of the family throughout the year. Additionally, during economically hard times the homegarden products are sold in the nearby market, thus contributing to income security.

Based on generation-old experience, the experiences of his forefathers passed on him and trial-error practice, farmers know which species grows best in his soil. Furthermore he knows best how to spatially arrange the species on the land. Such application of traditional wisdom to a large extent contributes towards sustainability of homegardens.

8.3 Threats to Sustainability

Many physical and functional characteristics of the homegardens of the tropics are dynamic because of the changes brought about by sociocultural and economic changes, population growth, product commercialization, and change in the market structure. Recent trend of homegarden intensification due to progressive commercialization in many societies is creating concerns on long-term sustainability of the system (Karyono 2000; Kehlenbeck 2007; Abdoellah et al. 2006). Due to commercialization there is evidence of erosion of homegarden biodiversity due to that fact the many owners tend to exclude and eliminate those species, which do not meet financial expectation. Additionally, commercialization of homegardens also affects several of its social functions. The study of Abdoellah et al. (2006), for example, found that commercial homegardens, in contrast to subsistence homegardens, keep less vacant space where children could find their playground. This is because the homegardener in commercial gardens wish to maximize utilization of their available land area for commercial production. The same study observed that commercial homegardens maintain more fencing to prevent 'trespassing' by neighbors and other community people. Such practice is quite unusual for non-commercial traditional homegardens. Hence impacting social functions negatively means reduction of chances of better sustainability. The other factors hampering homegarden sustainability include, but not limited to, heavy use of agrochemicals, dependency on hired labor, and risk of market fluctuation for commercial products, scarcity of land, high population density and impact of urbanization (Soemorowoto and Conway 1992; Karyano 1990; Michon and Mary 1994; Kehlenbeck and Maass 2004; Arifin et al. 1998). Nevertheless, the most important characteristics that will ensure future sustainability is the capacity of this farming system to cope with the changing circumstances rapidly. The diversity of the annual and perennial vegetation, high performance in household socioeconomy, traditional management, low dependence on external inputs, and closed nutrient cycling are the other characteristic features responsible for the stability of this traditional farming system.

9 Conclusion

Based on a rigorous literature review and my previous research experience across various agroecological regions of the country this paper provided insights into various compositional and functional issues of tropical homegarden with particular emphasis on Bangladesh. Although a number of studies are reported in literature dealing with a number of structural and functional issues, none touched new thrust areas. Hence, future efforts in scientific investigation on Bangladesh homegardens should focus on ecological basis in the functioning of the homegardens, carbon sequestration potentials and valuation of non-market benefits. Furthermore, the findings of this article showed that homegardens are managed based on traditional wisdom and internal inputs without any support from external sources. Hence future extension endeavors should be aiming at introducing high yielding verities of plant species and make those easily available with lower price. Government agencies and non-government organizations with their strong grassroots-level network should work closely with the farmers to provide advisory and material support.

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Arbuscular Mycorrhizal Fungi and Rhizobium to Control Plant Fungal Diseases

Mohd. Sayeed Akhtar, Zaki. A. Siddiqui, and Andres Wiemken

Abstract Soil microorganisms can be used to decrease the input of fertilizers, pesticides and other chemicals. Among soil microorganisms, arbuscular mycorrhizal (AM) fungi and *Rhizobium* spp. can promote plant growth and control plant fungal diseases. However these microorganisms are not yet used in commercial biocontrol products. Integration of arbuscular mycorrhizal fungus with *Rhizobium* sp. thus appears to be a promising approach for sustainable agriculture. Arbuscular mycorrhizal fungi and root-nodule bacterium *Rhizobium* are two root symbionts. Arbuscular mycorrhizal fungi increases soil nutrients and water absorption, while root-nodule bacteria fix atmospheric nitrogen and produce antibiotics and phytoalexins. These microbes modify the quality and abundance of rhizosphere microflora and alter overall microbial activity of the rhizosphere. They induce changes in the host root exudation pattern. A procedure for successful development of these microorganisms is required by selection and screening of efficient isolates. Knowledge of culture systems that are adapted to their establishment and multiplication is needed. Arbuscular mycorrhizal fungi provide specific niches for bacteria. Arbuscular mycorrhizal bacteria improve nutrient acquisition in plants. Arbuscular mycorrhizal bacteria may contribute to ability of arbuscular mycorrhizal fungi to inhibit pathogens, acquire mineral nutrients and modify plant root growth. Combined use of these microorganisms is more beneficial than their use alone. These symbionts also interact with other beneficial microorganisms synergistically and can be exploited for sustainable agriculture.

Keywords Arbuscular mycorrhizal fungi • Biocontrol • Fungal pathogens • Plant symbionts • Rhizobium

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1 Introduction

The beneficial plant-microbe interactions in the rhizosphere are primary determinants of plant health (Jeffries et al. 2003). Among the different plant symbionts arbuscular mycorrhizal (AM) fungi and root nodule bacterium *Rhizobium* spp. are the two important root symbionts. They play a key role in natural ecosystems and influence plant productivity, plant nutrition and disease resistance (Demir and Akkopru 2007). Mycorrhizas benefit the host through mobilization of phosphorus from non mobile sources, whereas *Rhizobium* fixes N_2 (Scheublin and Heijden 2006). The synergistic interactions of these microorganisms enhanced the abilibilty of major plant nutrients especially N and P (Barea et al. 2002).

Since these root symbionts, as well as the soil-borne pathogens, share common niche and influenced the growth of plant (Azcon-Aguilar and Barea 1996; Akhtar and Siddiqui 2008c) but it is very difficult to generalize their activity because of complex interaction taking place between the arbuscular mycorrhiza, fungal pathogens and *Rhizobium* (Dar et al. 1997; Aysan and Demir 2009). The main goal of this review is to focus on the effect of these root symbionts on the growth of plant and mechanisms involved in the suppression of fungal diseases.

1.1 Arbuscular Mycorrhizal (AM) Fungi

Arbuscular mycorrhizal (AM) fungi are ubiquitous in distribution and occur over a wide range of agro climatic conditions (Harrier and Watson 2004). They form symbiotic association with the roots of the 80% of the terrestrial plants (Smith and Read 2008). The AM fungi were previously included in the phylum Zygomycota, order Glomales (Redecker et al. 2000) but recently they have been placed into the phylum Glomeromycota (Schußler et al. 2001) comprising about 200 described species (Brachmann 2006). They are characterized by the presence of extra radical mycelium branched haustoria like structure within the cortical cells, termed arbuscules, and are the main site of nutrient transfer between the two symbiotic partners (Fig. 1) (Dickson and Smith 2001; Smith and Read 2008). The arbuscles formation generally provides a large surface area for nutrient transfer, due to the invagination of the host plasma membrane which is closely associated with the fine arbuscular hyphal branches (Dickson and Smith 2001). AM fungi colonize plant roots and penetrate into surrounding soil, extending the root depletion zone and the root system. They supply water and mineral nutrients from the soil to the plant while AM benefits from carbon compounds provided by the host plant (Siddiqui and Pichtel 2008; Smith and Read 2008). AM fungi are associated with improved growth of host plant species due to increased nutrient uptake, production of growth promoting substances, tolerance to drought, salinity and synergistic interactions with other beneficial microorganisms (Akhtar and Siddiqui 2008c).

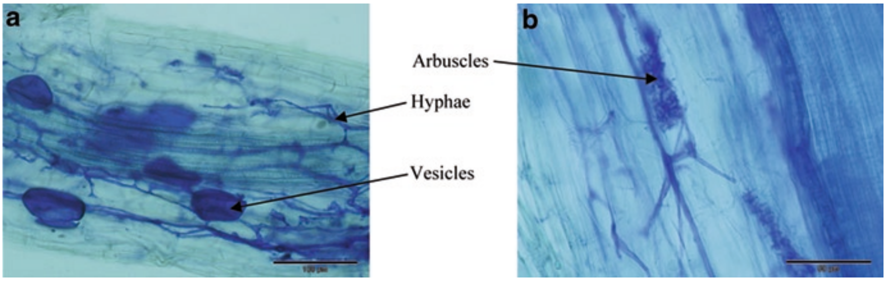

Fig. 1 Microscopic visualization of Arbuscular mycorrhizal fungi (**a**) showing vesicles and hyphae; (**b**) showing arbuscules in the maize root

Arbuscular mycorrhizal associations are the most frequent symbioses found in nature because of their broad association with plants and cosmopolitan distribution (Harley and Smith 1983). Agricultural practices such as tillage and fertilization can affect the structure of AM fungal communities; tilling can reduce either AMF spore density (Kabir et al. 1998) or AM fungal colonization of crops (McGonigle et al. 1990). The soil environment, plant physiological conditions and mycorrhizal can be greatly changed through different tillage or fertilization systems. Any agricultural operation that disturbs the natural ecosystem will have repercussions on the mycorrhizal system (Mosse 1986). The preceding crops affect growth and yield of subsequent crops (Karlen et al. 1994). The inclusions of non-mycorrhizal crops within rotations decrease both AM fungal colonization and yield of subsequent crops (Douds et al. 1997; Arihawa and Karasawa 2000). In addition to crop sequence, varietals selection, cultivation and following have been shown to affect mycorrhizal activity (Hetrick et al. 1996; McGonigle and Miller 2000). Sieverding (1991) found that in agroecosystems with monocultures, conventional tillage, high application of soluble phosphate, nitrogen and pesticides the number of fungal species decreases more than 50% in comparison to native ecosystems. No-tillage systems often are characterized by the accumulation of crop residues on the soil surface, leading to greater carbon, nitrogen and surface water compared to conventional tillage (Doran and Linn 1994). Mycorrhizal communities are site specific and each AMF species can be affected in several ways by different agricultural management practices, so generalization is difficult. The effect of fertilizers on AMF diversity has been studied in different agroecological conditions (Johnson 1993; Sieverding 1991). Johnson et al. (2003) have pointed out differences among AM fungal taxa in their strategies for the acquisition of nutrients. AM fungal colonization in roots change across different phenological stages of wheat (Mohammad et al. 1998; Schalamuk et al. 2004). Several studies have found temporal variation in the diversity of mycorrhizal communities of natural ecosystems (Lee and Koske 1994; Merryweather and Fitter 1998; Eom et al. 2000). Therefore, uses of AM fungi in the biocontrol for sustainable agriculture require knowledge of culture systems which may affect their establishment and multiplication in the field.

1.2 Root-Nodulating Bacteria

Symbiotic N_2-fixation is not only limited to the leguminous plants but also a number of non-leguminous plant can interact with N_2-fixing bacteria (Saikia and Jain 2007). Allen and Allen (1947) reported that among the Fabaceae, Mimosoideae (11.8%), Caesalpinioideae (3.3%) and Papilionoideae (84–89%) had the capacity to form nodules. However, another study showed that more than 90% of the Papilionoideae and Mimosoideae are nodulated whereas less than 25% of Caesalpinoideae form nodules (Hirsch et al. 2001). The root-nodule bacteria belong to genera *Rhizobium, Sinorhizobium, Bradyrhizobium, Mesorhizobium* and *Azorhizobium* collectively termed as rhizobia (Fig. 2) (Barea et al. 2005). These bacteria interact with legume roots leading to the formation of N_2-fixing nodules (Spaink et al. 1998; Sprent 2002). Rhizobial nodule formation is a complex process that requires a continuous and adequate signal exchange between the plant and the bacteria (Perret et al. 2000; Bartsev et al. 2004; Soto et al. 2006). In this symbiotic association, plant provides an energy source and ecological niche for the bacteria and in return bacteria provide a source of fixed nitrogen to plant (Vance and Johnson 1981).

The legumes and their association with *Rhizobium* spp. in broad sense have always been extremely important agronomically. In the Legume- *Rhizobium* interaction, once a plant has formed nodules, further nodulation is suppressed in other

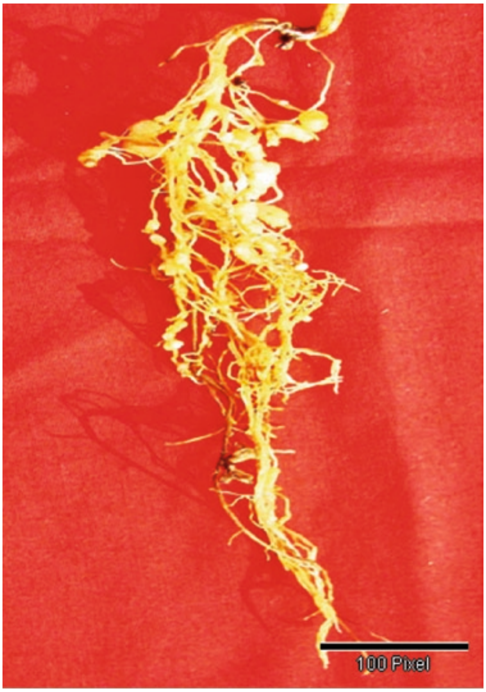

Fig. 2 Pea roots showing nodules

parts of the root system by a long distance signal exchange, which means that the nodulation is autoregulated (Okakira and Kawaguchi 2006). *Rhizobium* occurs free-living in the soil but does not fix nitrogen in this situation. Its association with leguminous roots and formation of nodules seems obligatory to fix nitrogen. The stages involved in root nodule formation include (1) recognition and attachment, (2) penetration and travel, (3) bacteroid formation and development of mature nodule. (1) in recognition and attachment variety of organic metabolites secreted by the roots of legume plants, the rhizobia migrate towards and grow in the rhizosphere and build up to high population density. A series of flavonoid signals are there in organic metabolites that lead to the exchange of recognition signals thus attracting specific rhizobia species to specific legume root-hairs. All species of *Rhizobium* (and *Bradyrhizobium*) possess specific adhesion protein called rhicadhesin on their surface. Rhicadhesin is a calcium-binding protein and binds calcium complexes on the surface of root hairs. Lectins, carbohydrate containing proteins, also contribute in *Rhizobium*-Legume attachment. (2) After attachment, the root hair curls as a result of the action of substances, excreted by the *Rhizobium* species called nod-factors. Some physiologists believe that curling is also affected by indole acetic acid. After curling of the root-hair, the bacteria penetrate and enter the root-hair and induce the plant to develop a cellulosic tube, called infection thread, which extends inward to the root-hair. The *Rhizobium* cells then spread within the infection thread, move into the underlying root cells, and are released into cytoplasm of the host cell through the action of an organizer produced by the interaction between the rhizobial polysaccharides and component of root cells. Nod factors now stimulate root cell division eventually leading to the development of the root nodule. (3) When the bacteria are released from the infection thread into the host cell cytoplasm, they get transformed into swollen, irregular-shaped, branched structures called bacteroids which then become surrounded singly or in small groups by a plant-derived membrane, called peribacteroid membrane, to form structures called 'symbiosome' (http://www.studentsguide.in/microbiology/biological-nitrogen-fixation/root-nodule-formation-in-rhizobium-legume-association.htm)

2 Mechanism of Fungal Disease Suppression

The persistence of fungal plant pathogens in the soil is the most important problem worldwide, often resulting in reduced yields and occasionally causes major crop damage. Agrios (2005) reported that more than thousands of fungi are known to cause diseases of plants and are common in soil, air and on plant surfaces throughout the world. The fungal pathogens that persist in the soil matrix and in residues on the soil surface, and are as the main cause for soil borne diseases. The soil is a reservoir of inoculum of these pathogens, the majority of which are widely distributed in agricultural soils. Damage to root and crown tissues is often hidden in the soil; thus, these diseases may not be noticed until the above ground parts of the plant are severely affected, showing symptoms such as stunting, wilting, chlorosis and death. Fungal diseases are difficult to control because they are caused by pathogens which can survive for long periods in the absence of the normal crop host, and often have a wide host range including weed species. The occurrence of AM fungi and plant pathogenic fungi in roots of different crops and their dependence for nutrition on the host generally result in the interaction of AM fungi, plant pathogenic fungi and host plant. Association of these organisms generally exert opposite effects on the host. Thus it is desirable to test the mutual effects of these organisms on plant growth and yield. Plant diseases can be controlled by manipulation of indigenous microbes or by introducing antagonists to reduce the disease-producing propagules (Linderman 1992). With the increasing cost of inorganic fertilizers and the environmental and public health hazards associated with pesticides and pathogens resistant to chemical pesticides, AM fungi may provide a more suitable and environmentally acceptable alternative for sustainable agriculture. Several reviews exploring the possibilities of AM fungi in the biocontrol of plant diseases include (Linderman (1994); Siddiqui and Mahmood (1995a); Azcon-Aguilar and Barea (1996); Mukerji (1999); Barea et al. (2005); Akhtar and Siddiqui (2008c)). Therefore, the interactions between different AM fungi and fungal pathogens vary with the host plant and the cultural system. Similarly, the protective behavior of *Rhizobium* against the plant diseases has also been reported by various workers (Perret et al. 2000; Bartsev et al. 2004; Barea et al. 2005; Soto et al. 2006). The interactions of these root symbionts with fungal pathogens have been summarized in tabular forms (Tables 1 and 2).

3 Reason for Reduced Damage of Fungal Pathogens by AM Fungi

Some of the reasons for reduced damage of fungal pathogens by AM fungi are as follows.

3.1 Improved Nutrient Status of the Host Plant

The obvious contribution to reduction of root diseases is increased nutrient uptake particularly phosphorus and other minerals, because AM symbiosis results in more vigorous plants and thus become more resistant or tolerant to pathogen attacks (Linderman 1994). Davis (1980) found this type of response on Thielaviopsis root-rot of citrus, where AM plants were larger than nonmycorrhizal plants until the latter were fertilized with additional phosphorus. Graham and Menge (1982) observed a similar effect, where AM fungi or added P reduced wheat take-all disease caused by *Gaeumannomyces graminis*, and speculated that enhanced P status of the plant causes a decrease in root exudates used by the pathogen for spore germination and infection. AM symbiosis increase uptake of P and increased P v in

Table 1 Effect of Arbuscular mycorrhizal fungi on the fungal disease of plants

AM fungi	Pathogenic fungus	Effect	Reference
Glomus intraradices	*Fusarium oxysporum* f. sp. *radicis-lycopersici*	AM fungus significantly reduced Fusarium root rot on tomato	Caron et al. 1985
G. fasciculatum	*Aphanomyces euteiches*	Reduced root rot on pea	Rosendahl 1985
G. mosseae	*F. oxysporum*	Significantly reduced Fusarium wilt on tomato and pepper	Al-Momany and Al-Raddad 1988
G. etunicatum *Glomus* sp.	*Pythium ultimum*	Prior or simultaneous inoculation of AM fungus with *P. ultimum* reduced disease severity on cucumber	Rosendahl and Rosendahl 1990
G. fasciculatum	*Macrophomina phaseolina*	Prior inoculation of AM fungus reduced disease on cowpea	Devi and Goswami 1992
Glomus sp., *G. fasciculatum,*	*Verticillium albo-atrum* *F. oxysporum* f. sp. *medicaginis*	Seedlings inoculated with AM fungi had lower incidence of wilt in alfalfa than did non-mycorrhizal species	Hwang et al. 1992
G. fasciculatum	*F. oxysporum*	Prior inoculation of AM fungus reduced colonization by pathogens and severity of disease on cowpea	Sundaresan et al. 1993
G. intraradices	*Pythium ultimum*	Reduced populations of *P. ultimum* on *Tagetes patula*	St-Arnaud et al. 1994
G. intraradices	*F. oxysporum* f. sp. *lycopersici*	Significantly reduced disease severity but is most effective when applied with *T. harizianum*	Datnoff et al. 1995
G. mosseae *G. vesiformae* *Scutellospora sinuosa*	*Verticillium dahliae*	Inoculation of AM fungi reduced disease indices in cotton	Liu 1995
G. fasciculatum	*Fusarium oxysporum*	Reduced wilt indices in chickpea	Rao and Krishnappa 1995
G. fasciculatum	*Fusarium udum*	Significantly reduced disease severity in pigeon pea	Siddiqui and Mahmood 1995b
G. margarita	*Fusarium udum*	Reduced wilt indices in pigeon pea	Siddiqui and Mahmood 1995c
Glomus sp.	*Sclerotium cepivorum*	AM fungi reduced white rot incidence and delayed disease development on onion	Torres-Barragan et al. 1996

(continued)

Table 1 (continued)

AM fungi	Pathogenic fungus	Effect	Reference
G. mosseae	*Fusarium udum*	Reduced disease severity on pigeon pea	Siddiqui and Mahmood 1996
G. mosseae	*Phytophthora nicotianae* var. *parasitica*	Reduced root necrosis, and necrotic root apices ranged between 63 and 89%	Trotta et al. 1996
Glomus intraradices	*Aphanomyces euteiches*	Reduced disease severity in pea	Kjoller and Rosendahl 1997
G. mosseae	*Fusarium solani*	Significantly reduced disease severity in chickpea	Siddiqui and Mahmood 1997
Glomus intraradices	*Aphanomyces euteiches*	Reduced disease severity in pea	Bodker et al. 1998
G. mosseae	*Fusarium udum*	Reduced disease severity in pigeon pea	Siddiqui et al. 1998
G. etunicatum	*F. oxysporum* f. sp. *lycopersici*	Reduced disease severity in tomato	Ozgonen et al. 1999
G. etunicatum	*F. oxysporum* f. sp. *lycopersici*	Reduced disease severity on tomato	Bhagawati et al. 2000
G. mosseae	*F. solani* *R. solani*	Significantly reduced severity of diseases in peanut	Elsayed Abdalla and Abdel-Fattah 2000
G. intraradices	*Rhizoctonia solani*	Defense response elicited by *R. solani* significantly suppressed by AM fungus in alfalfa	Guenoune et al. 2001
G. clarum	*Rhizoctonia solani*	Significantly reduced root necrosis and number of sclerotia on cowpea	Abdel-Fattah and Shabana 2002
Glomus sp. *G. proliferum,* *G. intraradices* *G. versiforme*	*Cylindrocladium spathiphylli*	AM fungi significantly increased growth and reduced disease severity in banana. *Glomus* sp. and *G. proliferum* caused greatest increase in plant growth compared to that caused by *G. intraradices* and *G. versiforme*	Declerck et al. 2002
G. mosseae *G. intraradices*	*P. parasitica*	*G. mosseae* was most effective in reducing disease symptoms produced by *P. parasitica* on tomato	Pozo et al. 2002
G. etunicatum *G. intraradices*	*R. solani*	Significantly reduced disease severity in micro-propagated banana	Yao et al. 2002
G. mosseae	*Fusarium chlamydosporium*	Reduced disease severity but best management was obtained when used with *T. viridae*	Boby and Bagyaraj 2003

G. intraradices *G. claroideum*	*Aphanomyces euteiches*	Reduced disease severity on pea but effects were more pronounced in plant inoculated with *G. intraradices* than with *G. claroideum*	Thygesen et al. 2004
G. fasciculatum	*F. oxysporum* f. sp. *ciceris*	Reduced the disease severity in chickpea	Siddiqui and Singh 2004
Glomus intraradices	*F. oxysporum* f. sp. *lycopersici*	Reduced severity of disease in tomato	Akkopru and Demir 2005
G. intraradices BEG12	*Rhizoctonia solani*	Significantly decreased epiphytic and parasitic growth of pathogen in tomato	Berta et al. 2005
G. mosseae	*Alternaria triticina*	Reduced percent infected leaf area on wheat	Siddiqui and Singh 2005
G. etunicatum BEG168	*F. oxysporum* f. sp. *cucumerinum*	AM fungus influenced secondary metabolites and increased wilt resistance in cucumber seedlings	Hao et al. 2005
G. mosseae	*C. orbiculare*	AM fungus had no significant effect on disease development	Chandanie et al. 2006
G. intraradices	*M. phaseolina*	Inoculation of AM fungus with *A. niger* and *Bacillus* (B22) caused a greater reduction in root-rot of chickpea	Akhtar and Siddiqui 2006
G. fasciculatum	*M. phaseolina*	Reduced disease severity in chickpea	Akhtar and Siddiqui 2007a
G. intraradices	*M. phaseolina*	Significantly reduced disease severity in chickpea	Akhtar and Siddiqui 2007b
G. mosseae, *G. etunicatum*, *G. fasciculatum* *Gigaspora margarita*	*Phytophthora capsici*	Inoculation of AM fungi significantly increased plant growth and reduced disease severity in pepper but *G. mosseae* reduced disease severity to a greater extent	Ozgonen and Erkilic 2007
G. intraradices	*M. phaseolina*	Combined inoculation of AM fungus with *Pseudomonas straita* and *Rhizobium* caused a greater reduction in the root-rot of chickpea	Akhtar and Siddiqui 2008a

(continued)

Table 1 (continued)

AM fungi	Pathogenic fungus	Effect	Reference
G. intraradices	*M. phaseolina*	Combined application of *G. intraradices* with *P. alcaligenes* and *B. pumilus* caused a greater reduction in the root-rot of chickpea	Akhtar and Siddiqui 2008b
G. mosseae	*Sclerotinia sclerotiorum*	Reduced the disease severity upto 10.3% on common bean	Aysan and Demir 2009
G. mossae	*R. solani*	Prior inoculation of AM fungus significantly reduced the disease severity of cucumber but the results were more pronounced when inoculated with plant growth promoting fungi	Chandanie et al. 2009
G. etunicatum, *G. mosseae*, *G. clarum*, *G. caledonium*, *G. fasciculatum*, *Gigaspora margarita*	*Sclerotium rolfsii*	Inoculation of all the AM fungi reduced the disease severity (37.8–64.7%) in pot condition while in field condition it varied from 30.6 to 47.2%	Ozgonen et al. 2010

Table 2 Effect of *Rhizobium* on the fungal disease of plants

Rhizobium	Fungus	Effect	Reference
Rhizobium meliloti	*Phytophthora megasperma* *Fusarium oxysporum*	Reduced the incidence of root-rot on alfalfa	Tu 1980
Rhizobium sp.	*M. phaseolina*	Seed treatment with *Rhizobium* significantly reduced the charcoal rot on soybean	Chakaraborty and Purkayastha 1984
Rhizobium sp.	*Fusarium solani* f. sp. *pisi*	Rhizobitoxine produced by *Rhizobium* reduced the pathogenic fungi on pea	Chakaraborty and Chakaraborty 1989
Rhizobium sp. *Bradyrhizobium* sp.	*M. phaseolina*	Inhibited the growth of *M. phaseolina* on sunflower and mung bean	Hussain et al. 1990
Rhizobium meliloti	*F. oxysporum Fusarium solani*	Seed treatment significantly controlled infection of *Fusarium oxysporum* and *Fusarium solani* on tomato and okra	Farzana et al. 1991
Bradyrhizobium sp.	*M. phaseolina*	Prior inoculation of *Bradyrhizobium* sp. reduced the damage caused by pathogen	Siddiqui and Husain 1992
R. meliloti *R. leguminosarum* *B. japonicum*	*M. phaseolina* *R. solani* *F. solani*	Use of Rhizobial strains as seed dressing or soil drench reduced the infection of pathogen in both leguminous and non leguminous plants	Haque and Ghaffar 1993
Bradyrhizobium japonicum	*Fusarium oxysporum* f. sp. *ciceris*	Reduced the disease severity on chickpea	Siddiqui and Mahmood 1994
Bradyrhizobium sp.	*R. solani*	Inoculation of *Brady- rhizobium* reduced the mycelial growth and sclerotia formation *in vitro*	Kelemu et al. 1995
Bradyrhizobium japonicum	*Fusarium udum*	Reduced the disease severity on pigeon pea	Siddiqui and Mahmood 1995b
Rhizobium leguminosarum	*Fusarium solani*	Reduced the population density of *F. solani* on common bean	Dar et al. 1997
Bradyrhizobium sp.	*Fusarium solani*	Reduced the damage caused by pathogen on chickpea	Siddiqui and Mahmood 1997
Rhizobium	*Bothytis fabae*	Significantly reduced the disease severity on *Vicia faba*	Rabie 1998

(continued)

Table 2 (continued)

Rhizobium	Fungus	Effect	Reference
R. leguminosarum	*Phytophthora clandestina*	Reduced the disease severity on clover	Simpfendorfer et al. 1999
Rhizobium	*Fusarium oxysporum* *Sclerotium rolfsii*	Seed treatment with *Rhizobium* in effective in controlling *Fusarium oxysporum* and *Sclerotium rolfsii* diseases and also increased the plant growth on lentil	Hossain et al. 1999
Rhizobium sp.	*Fusarium oxysporum* f. sp. *pisi*	Prior inoculation of *Rhizobium* sp. reduced the damage caused by pathogen than simultaneous inoculation on pea in different soil types	Siddiqui et al. 1999
Bradyrhizobium japonicum	*Fusarium udum*	Reduced the disease severity on pigeon pea	Siddiqui and Mahmood 1999
Rhizobium sp.	*F. oxysporum*	Seed bacterization with *Rhizobium* reduced the no. of infected pea in infected soil	Kumar et al. 2001
Rhizobium leguminosarum	*Fusarium oxysporum, Pythium ultimum Rhizoctonia solani*	Significantly inhibits the growth of fungal pathogens. It inhibits the growth in 14.65–16.03% for *R. solani*, 14.62–30.35% for *P. ultimum* isolates and 14.58–29.75% for *F. oxsporum* on bean	Ozkoc and Deliveli 2001
R. tropici	*F. oxysporum* f. sp. *phaseoli* *F. solani* *R. solani*	Reduced the root-rot disease on bean	Estevez de Jensen et al. 2002
Bradyrhizobium sp.	*Macrophomina phaseolina.*	Out of ten, three *Bradyrhizobium* sp. showed the antifungal activity against the *M. phaseolina* on groundnut	Deshwal et al. 2003
Rhizobium leguminosarum	*Fusarium oxysporum* f. sp. *lentis*	Culture filtrate of bacterium protects the lentil against the *Fusarium oxysporum*	Essalmani and Lahlou 2003
Rhizobium sp. (Thal-8)	*A. alternata*, *Fusarium* sp., *A.* rabiei, *Dreachslera* sp., *Curvularia* sp.	Significantly reduced the growth of pathogenic fungi 3–54% *in vitro* condition	Sharif et al. 2003
Rhizobium leguminosarum	*Pythium* spp.	Reduced the severity of damping off on pea and sugar beet	Bardin et al. 2004

Rhizobium sp.	*Fusarium oxysporum* f. sp. *ciceris*	Increased the growth and reduced the disease severity in chickpea	Siddiqui and Singh 2004
Rhizobium sp.	*S. rolfsii*	Reduced the severity on disease on ground nut	Ganesan et al. 2007
Rhizobium sp.	*Pythium* spp.	Seed treatment with *R. leguminosarum* bv. *viceae* significantly reduced incidence of damping off on pea and lentil	Huang and Erickson 2007
Rhizobium strains (BINAR P36 and BINAR P6)	*Fusarium oxysporum*	Seed treatments with *Rhizobium* strains significantly reduced the foot and root-rot disease on bush bean	Khalequzaman and Hossain 2007
Rhizobium strains (BINAR P36 and BINAR P6)	*Fusarium oxysporum*	Seed treatments with *rhizobium* strains significantly reduced the foot and root-rot disease on bush bean	Khalequzaman and Hossain 2008
Rhizobium sp.	*M. phaseolina*	Reduced the root-rot disease severity on chickpea	Akhtar and Siddiqui 2008a
Rhizobium sp.	*F. udum*	Inoculation of *Rhizobium* significantly reduced the wilting on pigeon pea but the results were more pronounced when applied in combination with PGPR	Siddiqui et al. 2008
Sclerotinia sclerotiorum	*R. leguminosarum* biovar *phaseoli*	Treatment with *Rhizobium* reduced the disease severity (24.1%) but the results were more pronounce when used with *G. mosseae* on common bean	Aysan and Demir 2009
Rhizobium sp.	*Fusarium oxysporum*	Significantly reduced the Fusarium wilt on Pigeon pea	Siddiqui and Shakeel 2009
Rhizobium sp.	*Fusarium oxysporum* f. sp. *lentis*	Significantly reduced the Fusarium wilt on lentil but the results were more pronounced when *Rhizobium* sp. was used with *B. pumilus* and *P. alcaligenes*	Akhtar et al. 2010

plant reduce disease severity caused by *Aphanomyces euteiches* in pea (Bodker et al. 1998). Declerck et al. (2002) suggested a similar effect whereby AM fungi or added P reduced root-rot of bananas caused by *Cylindrocladium spathiphyylii*. It has been hypothesized that direct competition between root pathogens require host nutrients for reproduction and development and this competition may be the cause of their inhibition (Dehne 1982; Smith 1988). Greater tolerance of AM plants is also attributable to increased root growth and phosphate status of the plant (Cameron 1986). In addition to P, AM fungi can enhance the uptake of Ca, Cu, Mn, S and Zn (Pacovsky et al. 1986; Smith and Giananizzi-Pearson 1988). Host susceptibility to pathogens and tolerance to disease can be influenced by the nutritional status of the host and the fertility status of the soil (Cook and Baker 1982). Increase in plant growth after root colonization by AM fungi is due to improvement in the mineral nutrient status of host plant. Depending on the host plant and AM fungus isolate, colonization of the root system can increase phosphorus nutrition and other mineral nutrients (Clark and Zeto 2000). However, in some cases enhanced mineral nutrition of mycorrhizal plants has no affect against pathogens (Graham and Egel 1988). Therefore, enhanced mineral nutrition of AM plants does not account for all protection conferred by AM fungi to host plant (Caron et al. 1986a).

3.2 Change in Root Growth and Morphology

The colonization by AM fungi results in morphological changes to the root, leading to an increased surface area of root (Aguin et al. 2004). Roots offer structural support to the plants and function in absorption of water and supply mineral nutrients for a wide range of microorganisms (Curl and Truelove 1986). Changes in root morphology will ultimately affect the plant's responses to other organisms (Yao et al. 2009). AM fungal-colonized roots are more highly branched, i.e., the root system contains shorter, more branched, adventitious roots of larger diameters and lower specific root lengths (Schellenbaum et al. 1991; Berta et al. 1993). The AM inoculated plants possess a strong vascular system, which imparts greater mechanical strength to diminish the effects of pathogens (Schonbeck 1979).

Dehne et al. (1978) observed increased lignifications in the endodermal cells of mycorrhizal tomato and cucumber plants and speculated that such responses may account for reduced incidence of Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*). Becker (1976) reported a similar effect on pink root of onion (*Pyrenochaeta terrestris*). Mycorrhizal plants produced wound-barriers at a faster rate than non-mycorrhizal plants and increased wound barrier formation inhibited *Thielaviopsis* black root-rot of mycorrhizal holly (*Ilex crenata*) plants (Wick and Moore 1984). The AM fungi reduce disease severity caused *Cylindrocarpon destructans* in strawberry (Paget 1975) and these examples emphasize the significance of AM fungi in bioprotection against fungal pathogens.

3.3 Competition for Colonization Sites and Host Photosynthates

AM fungi and soil-borne plant pathogens occupy similar root tissues and there may be direct competition for space if colonization is occurring at the same time (Smith 1988). If AM fungi and plant pathogens are colonizing the same host tissues there may be competition for space because both usually develop within different cortical cells of roots (Azcon-Aguilar and Barea 1996). Davies and Menge (1980) observed localized competition between AM fungi and *Phytophthora*. They observed reduced development of *Phytophthora* in AM-colonized and adjacent uncolonized root systems, and pathogens never penetrated arbuscule-containing cells (Cordier et al. 1996). Similarly *Aphanomyces* was suppressed on pea roots by AM fungi only when the two organisms were present on the same root (Rosendahl 1985). Vigo *et al.* (2000) observed that the numbers of infection sites were reduced within mycorrhizal root systems and colonization by the AM fungus had no effect on the spread of necrosis. AM fungi are dependent on the host as a carbon source and 4–20% of the host net photosynthate is transferred to the AM fungus (Smith and Read 2008).

3.4 Microbial Changes in the Mycorrhizosphere

The roots colonized by AM fungi differ from non-mycorrhizal roots in terms of microbial community composition of the rhizosphere (Marschner et al. 2001). These differences have been attributed to alterations in root respiration rate and quality and quantity of exudates. Plant root systems colonized by AM fungi differ in their effect on the bacterial community composition within the rhizosphere and rhizoplane. The number of facultative anaerobic bacteria, fluorescent pseudomonads, *Streptomyces* species and chitinase producing actinomycetes differ depending on the host plant and the isolate of AM fungus (Harrier and Watson 2004). In addition, extra radical hyphae of AM fungi provide a physical or nutritional substrate for bacteria. AM symbiosis can also cause qualitative and quantitative changes in rhizospheric microbial populations; the resulting microbial equilibria could influence the growth and health of plants. These changes may result from AM fungus-induced changes in root exudation patterns (Azcon-Aguilar and Bago 1994; Smith et al. 1994; Bansal et al. 2000). Changes in microbial populations induced by AM formation may lead to stimulation of the microbiota which may be antagonistic to root pathogens. AM establishment can change both total microbial populations and specific functional groups of microorganisms in the rhizoplane or the rhizosphere soil (Meyer and Linderman 1986; Linderman 1994). Numbers of pathogen-antagonistic actinomycetes were greater in the rhizosphere of AM plants than in nonmycorrhizal controls (Secilia and Bagyaraj 1987). The authors showed that pot cultures of *G. fasciculatum* harbored actinomycetes antagonistic to *F. solani* than those of non-mycorrhizal plants. Other studies indicate that pathogen suppression by AM fungi involves changes in mycorrhizosphere microbial populations. Caron et al. (1986a,b,c) showed a reduction in Fusarium populations in mycorrhizosphere soil of tomatoes and a corresponding reduction in root-rot in AM plants compared with non-AM plants, probably due to the increased antagonism in the AM mycorrhizosphere.

AM fungi provide numerous benefits to their hosts (Harrier and Watson 2004). In addition, AM fungi provide specific niches such as spores, extra radical hyphae and intraradical mycelia for population of bacteria (Schußler 2002). It seems that bacteria associated with AM fungal spores play an important role in the development of AM fungi. Those AMB (Arbuscular mycorrhiza associated bacteria) that help in the development of mycorrhizal symbiosis are termed as Mycorrhiza Helper Bacteria (MHB) (Garbaye 1994). It has been suggested that AMB can also function as Plant Growth Promoting Bacteria (PGPB) because they improve the nutrient acquisition in plants (Artursson et al. 2006). Some AMB are multifunctional and production of extracellular enzymes and bioactive compounds are likely mechanisms for their multifunctional activities (Bharadwaj et al. 2008a) and AMB may contribute to ability of AM fungi to inhibit pathogens, acquire mineral nutrients and modify plant root growth.

3.5 Activation of Plant Defense Mechanisms

The activation of specific plant defense mechanisms as a response to AM colonization is an obvious basis for the protective behavior of AM fungi. The elicitation, via an AM symbiosis of specific plant defense reactions, could predispose the plant to an early response to attack by a root pathogen (Gianinazzi-Pearson et al. 1994). In relation to plant defense relevant compounds include phytoalexins, enzymes of the phenylpropanoid pathway, chitinases, β-1,3-glucanases, peroxidases, pathogenesis-related (PR) proteins, callose, and phenolics (Gianinazzi-Pearson et al. 1994). Phytoalexins are low-molecular-weight, toxic compounds usually accumulating with pathogen attack and are released at the sites of infection (Morandi et al. 1984; Morandi 1996). Both phenylalanine ammonium-lyase (PAL), the first enzyme of the phenylpropanoid pathway, and chalcone isomerase, the second enzyme specific for flavonoid/isoflavonoid biosynthesis, increased in amount and activity during early colonization of plant roots by AM fungi (Lambais and Mehdy 1993; Volpin et al. 1994, 1995). These results suggest that AM fungi initiate a host defense response which is subsequently suppressed. Chitinases are little or only transiently induced by AM colonization (Dumas-Gaudot et al. 1992a,b). It has been reported that increased levels of chitinase activity are only detected in AM roots at the beginning of colonization (Spanu et al. 1989; Bonfonte-Fasolo and Spanu 1992; Lambais and Mehdy 1993). A decrease in β-1,3 endoglucanase activity has also been reported at specific stages during mycorrhiza development (Lambais and Mehdy 1993). These observations suggest a systemic suppression of the defense reaction during the establishment of the AM association. PR proteins are synthesized only locally and in very low amounts during AM colonization, although these molecules were regularly distributed around the arbuscular hyphae (Balestrini et al. 1994). The increased lignification of root endodermal cells induced by AM colonization has been suggested to play an important in the plant defense mechanism (Dehne

1982). However, these compounds could sensitize the root to pathogens and enhance mechanisms of defense to subsequent pathogen infection; the results of Benhamou et al. (1994) strengthened this hypothesis. It was evident from their results that mycorrhizal carrot roots afford increased protection against *Fusarium oxysporum* f. sp. *chrysanthemi*. In mycorrhizal roots, growth of the pathogen was usually restricted to the epidermis and cortical tissues, whereas in non-mycorrhizal roots the pathogen developed further, infecting even the vascular stele. Fusarium hyphae within mycorrhizal roots exhibited a high level of structural disorganization, characterized by the massive accumulation of phenolic-like compounds and the production of chitinases. This reaction was not induced by non-mycorrhizal roots, suggesting that the activation of plant defense responses by mycorrhiza formation provides a certain protection against the pathogen (Azcon-Aguilar and Barea 1996). These results need to be confirmed on different plants, and must clearly show that AM infection makes the root more responsive to pathogen attack, i.e., promoting a quicker and stronger reaction against the pathogen.

AM fungal spores appear to host certain sets of AMB (Arbuscular mycorrhiza associated bacteria) of which some can contribute to resistance by AM fungi against plant pathogens (Bharadwaj et al. 2008b). During mycorrhization formation, modulation of plant defense responses occurs potentially through cross-talk between salicylic acid and jasmonate dependent signaling pathways. This modulation may impact plant responses to potential enemies by priming the tissues for a more efficient activation of defense mechanisms (Pozo and Azcon-Aguilar 2007).

In contrast to the weak defense response towards AM fungi found in AM hosts, it is noteworthy that in myc- pea mutants, AM fungi trigger a strong resistance reaction. This suggests that the AM fungi are able to elicit a defense response, but that symbiosis-specific genes somehow control the expression of the genes related to plant defense during AM establishment (Gianinazzi-Pearson et al. 1994, 1995, 1996). It is curious, in this context, that the constitutive expression of several PRs in tobacco plants did not affect either the time course or the final level of colonization by *Glomus mosseae*, which was only reduced in plants constitutively expressing an acidic isoform of tobacco PR-2, a glucanase (Vierheilig et al. 1996).

4 Reason for Reduced Damage for the Fungal Pathogens Caused by Root-Nodule Bacteria

Some of the possible reasons for reduced fungal pathogens are as follows.

4.1 Physiological and Biochemical Changes

The root-nodule bacteria which fix atmospheric nitrogen are reported to produce toxic metabolites inhibitory to many plant pathogens (Haque and Ghaffar 1993). *Rhizobium japonicum* secretes rhizobitoxine, which is inhibitory to charcoal root fungus, *Macrophomina phaseolina* (Chakaraborty and Purkayastha 1984). Chakaraborty and Chakaraborty (1989) reported an increased level of phytoalexin (4-hydroxy-2,3,9-trimethoxypterocarpan) when pea seeds were bacterized with *Rhizobium leguminosarum* prior to inoculation with *Fusarium solani* f. sp. *pisi*. This phytoalexin may have an important role in cross-protection against many pathogens. Breil et al. (1996) reported that *Rhizobium* spp. have the capability to produce trifolitoxin having antimicrobial activity against the pathogens. Roslycky (1967) reported production of an antibiotic bacteriocin by rhizobia. Some antibiotics properties of rhizobia have also been reported by others workers (Drapeau et al. 1973; Tu 1980).

4.2 Change in Root Growth and Morphology

Rhizobium had the ability to increase the nodulation in leguminous plant which increases in plant vigor besides protecting roots from the attack of pathogen (Tilak et al. 2006; Huang and Erickson 2007). Kumarasinghe and Nutman (1977) reported that the root hairs treated with Rhizobia revealed thickening of the walls which was sometimes associated with arrays of vesicles of neighboring cytoplasm. The nodulation process in rhizobia-legume symbiosis requires a sequence of highly regulated and coordinated events, initiated by an exchange of specific signaling compounds between both partners. Subsequently, rhizobia invade the host by means of an infection thread formed from curled root hairs that grows towards an emerging meristematic nodule zone in the root cortex (Albrecht et al. 1999).

4.3 Activation of Plant Defence Mechanisms

The accumulation of phytoalexins is observed in plants treated with *Rhizobium* possess biological activity against fungal pathogens (Dar et al. 1997). Arfaoui et al. (2007) reported that *Rhizobium* spp. induced the expression of defense-related genes involved in phytoalexin synthesis and made the seedlings primed for subsequent infections by pathogen. Similar, results have been also reported in *Rhizobium* treated alfalfa against *Colletotrichum trifolii* and *Phoma medicaginis* (Boddu et al. 2004; Volpin et al. 1995). Saunders and O'Neill (2004) observed an increase in the accumulation of defense related genes in alfalfa seedlings that had been challenged with *Colletotrichum trifolii*. It has obvious from various reports that the defense related genes has been often associated with disease resistance in many pathosystems which confers the findings of earlier workers (Ellis et al. 2002; Pritsch et al. 2000). Phenolic acids are carbon-based compounds present in plants and are known to confer resistance either directly or indirectly through activation of post infection responses in the hosts (Harborne 1988). The presence of Phenolics were observed in *Rhizobium* treated seedlings against the fungal pathogens (Nicholson and

Hammerschmidt 1992; Mishra et al. 2006). Phenolics had the ability to bind to protein thus forming soluble and insoluble complexes (Hagerman and Robbins 1987). This phenolic-protein interaction is responsible for the putative function of phenolics in plant defense mechanism (Mole and Waterman 1987). Accumulation of phenolics viz. gallic, ferulic and tannic has the antifungal and antioxidative properties (Madhavi et al. 1997). Similarly, Cinnamic acid is a key product of the phenylpropanoid pathway synthesized from phenylalanine through catalysis by phenylalanine ammonia lyase (PAL) and plays a vital role in host resistance under pathogenic stress (Singh and Prithviraj 1997).

Plant defenses against fungal pathogens are dependent upon an early recognition of the invader and the initiation of appropriate signaling processes, which may be play an important role in the activation of multi-cascade defense-responses. The defense related genes are responsible for encoding variety of proteins that might be controlling the secondary metabolism, pathogenesis related proteins and regulatory proteins that control the expression of other defense-related genes involved in signal transduction pathways (Dixon et al. 1994; Ramalingam et al. 2003). The interaction between plant pathogens and their hosts is a complex process that involves a continuous exchange of information between the two organisms (Dixon and Lamb 1990). Enhancement of resistance can be accomplished by inoculating the plant with an inducer before it is infected by a pathogen. Arfaoui et al. (2006) reported that pre-treatment of chickpea seeds with *Rhizobium* spp. reduced the incidence of Fusarium wilt and induced significant increases in the activity of several defense-related enzymes phenolic compounds (Arfaoui et al. 2005).

5 Inoculum Production

AM fungi and *Rhizobium* had the capability to increase soil nutrients and water absorption as plant symbionts and also protect the plants from root pathogens under different pathosystems (Akhtar and Siddiqui 2008a; Avis et al. 2008). Beside these microorganisms also offers an alternative to chemical control and now used as a potential tool in the moderns agricultural system.

The main obstacle is to produce large quantities of inoculum because of their obligate nature. Traditionally, AM fungi are propagated through pot-culture. Starting fungal inoculum, usually made of spores and colonized root segments, are incorporated to a growing substrate for seedling production (Brundrett et al. 1996). The fungi spread in the substrate and colonize root seedlings. Both colonized substrates and roots can then serve as mycorrhizal inoculum. Bagyaraj (1992) found that mixture of Perlite: Soilrite mix (1:1 v/v) is the best substrate and the *Chloris gayana* (Rhodes grass) to be the best host for the mass propagation of mycorrhizal inocula, while the pesticides Captan and Furadan added to the pot cultures at half the recommended level checked contaminants with no effect on the mycorrhizal fungi. This technique is very useful for the production of clean mycorrhizal inoculum with high potentiality in a short span of time. Soil-less similar culture systems such as aeroponic cultures enable the production of cleaner spores and facilitate uniform nutrition of colonized plants (Jarstfer and Sylvia 1999). The successful propagation of some AM fungal strains on root-organ culture allowed the cultivation of monoxenic strains that can be used either directly as inoculum or as starting inoculum for large-scale production (Fortin et al. 2002).

The large-scale production of AMF inoculum, requires control and optimization of both host growth and fungal development. The microscopic sizes of AMF, together with the complex identification processes also contribute to the pitfalls of inoculum propagation. The inoculum propagation process entails the following stages.

1. Isolation of AMF pure culture strain.
2. Choice of a host plant.
3. Optimum growing conditions

In vitro bulk production of AMF inoculum is promising, offering clean, viable, contamination-free fungi. The cost of in vitro inoculum may appear prohibitive compared to the cost of a greenhouse-propagated one, but its use as starting inoculum is a warranty of purity. Their common purpose is mainly to provide research and industry scientists with pure and reliable material for starting inoculum production for both fundamental researches and applied technologies (Dalpe 2004). Mass production of AM fungi has been achieved with several species with increased spore production on monoxenic cultivation. Chabot et al. (1992) were able to produce 25 spores/ml in 4 months incubation time. St-Arnaud et al. (1996) produced 1000 spores/ml in 3–4 months time. Similarly, Douds (2002) produced 3250 spores/ml in 7 months while Adholeya (2003) was able to produce 3000 spores/ml in 3 months incubation time through monoxenic based inoculum production.

Fungal viability and mycorrhizal efficiency can be maintained for several months at room temperature (68 – 77°F) especially when semi-dry inocula are kept in their plastic containers or packaging. Long-term storage (up to 1 – 2 years) may be conducted at 41°F cold temperature storage. More sophisticated and expensive preservation techniques are performed by research culture collections. These include the maintenance of inoculum on living plant-host grown on sterile growth substrate with regular check for mono-specificity of the cultivated strains, storage in liquid nitrogen tanks (Douds and Schenck 1990), and freeze-drying under vacuum.

Similarly, the presence of Rhizobia in the rhizosphere presumably protects the host roots from pathogens, besides fixing atmospheric nitrogen. The use of Rhizobia with mycorrhizal fungi is more beneficial for reducing the damage caused by pathogens (Akhtar and Siddiqui 2008a). The most common inoculums production is to incorporate the Rhizobial cells with a carrier that can act as sort of coating for the legume seeds as they are sown. This coating may often be peat, charcoal base an enable both prolonged survival of the inoculums (both in storage and in the field) and close contact between legume seed and inoculums. Sometime the carrier is stuck to the seed with gum Arabic or similar resinous compounds as a true seed coating. Sometimes applied in granules and sometime sprayed into the seed furrows as a slurry suspension.

6 Conclusion

The use of AM fungi and Rhizobium will also increase the nitrogen and phosphorus uptake and in turn reduce the use of agrochemicals. The agrochemicals are very costly and had side effects on human health and environment. With the use of these symbionts farmers can save the capital and can achieve sustainable agriculture. For effective and persistent disease management the need is to evaluate these symbionts in the natural system under field conditions. The use of mixed inoculum of AM fungus and *Rhizobium* can be more effective and give better results than use of a single species. Selection of superior indigenous AM fungus and *Rhizobium* may have an adaptive advantage to the soils and environment in which pathogen and host co-occur as compared to non-indigenous mycorrhizal symbionts. Moreover, bioprotection of fungal diseases by mycorrhizal fungi and Rhizobia is a complex process which can be accomplished by a multigenic interaction between hosts and biocontrol agents and pathogens. The challenge for developing more sustainable production systems in the future includes gaining a better understanding for the mechanisms involved and the plant, fungal pathogens, symbionts and environmental factors together dictate the scale and timing of their expression.

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Sustainable Crop Production using Saline and Sodic Irrigation Waters

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Abstract Irrigation water is one of the most critical and scarce resource for agricultural production in arid and semiarid regions. Enhancing productivity in arid regions largely depends upon the ability to enlarge water resource by better rainwater management and development of groundwater. The lack of good water supplies for irrigated agriculture in now becoming a major issue that is forcing farmers to use low quality waters. Nonetheless injudicious use of sodic and saline waters poses grave risks to soil health by deteriorating soil physical, chemical and biological properties. Development of salinity, sodicity and toxicity problems not only reduces crop productivity but also limits crop choice. It is therefore imperative that irrigation development plans are carefully drawn and executed to sustain crop production and to minimize salinization and deterioration of soil physical conditions over the long-term. Alternative options have now emerged to safely use waters otherwise designated unfit. This has led to the replacement of too conservative water quality standards by site-specific guidelines where factors like soil texture, rainfall and crop tolerance have been given due consideration. Nevertheless, appropriate selection of crops, improvement in water and fertility management, maintenance of soil structure and tail water return systems are still necessary. Examples of the available technologies and practices for sustaining irrigation with these waters are given in this article. Economic development, social preferences and resource endowments are region-specific, and are thus expected to influence the selection and adoption of technology packages. Although the emphasis is placed on experiences in India, such practices are appropriate for many other arid and semi-arid regions where irrigated agriculture is confronting the similar challenges.

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Abbreviations

EC	Electrical conductivity
ECe	EC of the saturated extract
RSC	Residual sodium carbonate
ESP	Exchangeable sodium percentage
SAR	Sodium adsorption ratio

1 Introduction

Sustained development of surface and groundwater resources for irrigation plays a vital role in the production and productivity of food and fiber crops in arid and semi-arid climates. One major problem facing irrigated agriculture nowadays is the dwindling supplies of good quality water. Large parts of Australia, the Indian subcontinent, China, countries in the Middle East, parts in north and south America and Europe and substantial parts of North Africa lack sufficient supplies of good quality irrigation water (Seckler et al. 1998). Generally, the areas characterized by water scarcity are underlain with aquifers of poor quality (Minhas and Tyagi 1998) which can be saline, sodic or saline-sodic. Saline groundwater usually exist in the areas with high aridity, with high water table and water logged areas and in the vicinity of seawater in coastal regions, while sodic waters are prevalent in semi-arid regions with annual rainfall of 500–700 mm. With limited access to surface water supplies, many farmers in arid and semi-arid regions of the world are left with no other alternative except to utilize these poor quality ground waters for supplemental irrigation. Moreover, many more areas with good quality aquifers are threatened by contamination from nitrates and pesticide residues (Grattan and Oster 2003; Shah and Deb Roy 2002). With large scale installations of surface/sub-surace drainage systems, the volumes of saline drainage effluents are also increasing. In land locked areas, the only alternative is to promote their in-situ utilization.

Improper management of poor quality waters, without careful regard to their overall salinity and ionic composition of the irrigation water sources pose grave risks to soil conditions and the environment (Minhas and Gupta 1992; Gupta and Abrol 2000; Minhas and Bajwa 2001; Choudhary et al. 2004). Estimates are that about 10 m ha of irrigated land in the world suffers from secondary salinization and sodification (Szabolcs 1994). Excessive use of even good quality canal water has led to increased pace of secondary salinization and turned large areas along the Westside of the San Joaquin Valley in California to be unproductive (Wichelns and Oster 2006). This occurs when saline water tables are close to the surface and over irrigation will cause these water tables to rise into the crop root zone. A similar situation occurs in the northwest plains of Indo-Gangetic basin (Minhas and Samra

2003) and China's yellow river basin (Gupta and Abrol 2000; Qadir et al. 2006). Salt and irrigation induced land degradation is also occurring in the Aral Sea Basin in Central Asia: considered to be the largest environmental change caused by humanity in recent times (Cai et al. 2003).

Projections indicate the global need to produce more food and fiber for the world's expanding population with decreasing supplies of good quality water. Such an increased demand will lead to further increases in the use of marginal-quality water and land resources (Bouwer 2000; Gupta and Abrol 1990). Particularly vulnerable are less-developed, arid and semiarid countries, where problems of soil and water quality degradation are common (Sharma and Minhas 2005; Qadir et al. 2007).

This review includes irrigation strategies that foster sustainable crop production as well as alleviating environmental, off-site hazards of using saline and sodic waters. Emphasis is placed on research experiences in India. Salinity/sodicity in this region is characterized by high bicarbonates and differs from other places in the world where saline/sodic conditions are dominated by chloride or sulfate (Grattan and Oster 2003). Therefore there are similarities among remedial strategies, but there are clear differences regarding high pH and high HCO_3^-. Because many arid and semi-arid places in the world, other than India and Asia, are characterized by this type of carbonate-dominated salinity and sodicity, it is important to review such management strategies to address this set of problems.

2 Salinity and Sodicity

The most important criterion for evaluating given water is its total salt concentration. The quantities of salts dissolved in irrigation water are usually expressed in terms of EC, $mg\,L^{-1}$ (ppm) or $mmol_c\,L^{-1}$, the former being most popular because of ease and precision in its measurement. Some of the irrigation waters have a tendency to produce alkalinity/sodicity hazards depending upon the absolute and relative concentrations of specific cations and anions contained in them. The parameters for knowing the potential of irrigation waters to create these hazards are: Sodium Adsorption Ratio $[SAR = (Na)/\sqrt{(Ca + Mg)/2}]$; Residual Sodium Carbonate $[RSC = (CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})]$, concentrations expressed in $mmol_c\,L^{-1}$ and new adjusted SAR denoted as (adj. R_{Na}) [adj. $R_{Na} = Na/\sqrt{[(Ca_x + Mg)/2}$, where Ca_x represents the Ca in applied water modified due to salinity (ionic strength) and HCO_3^-/Ca^{2+} ratio] (Ayers and Westcot 1985). Ground waters having high contents of toxic ions such as boron, fluoride, nitrate, selenium etc. also become problematic for irrigating crops and have consequence of entering human food chain.

Information on chemical composition is necessary but alone is not sufficient to decide its potential use for crop production at a specific location. Several other factors such as nature of crop to be grown, soil characteristics (texture and mineralogy), climate and other water management and cultural practices are equally important and should be taken into consideration. Based on the characteristic features of majority of ground waters and the above indices those describe the nature of hazards on soils and crops, poor quality irrigation waters have been broadly grouped into saline and sodic waters.

There is a clear distinction between impacts of soil salinity and sodicity; the former being related to salt concentration and the latter to salt composition. Salinity refers to the concentration of salts in the irrigation water or soil that is sufficiently high to adversely affect crop yields or crop quality. Sodicity, on the other hand, is related to the proportion of sodium in the water, or adsorbed to the soil surface, relative to calcium and magnesium. The higher this proportion, the higher the sodicity. Sodicity can cause dispersion due to poor structural stability in water contributing to the deterioration of soil physical properties. Physical degradation of soils is manifested through increased surface crusting that impacts seedling emergence, reduced infiltration affecting water holding capacity of soil profile, increased soil strength impacting root penetration and reduced aeration resulting in anoxic conditions for roots. Due to these effects, making tillage and sowing operation becomes more difficult (Oster and Jaywardane 1998). In irrigated agriculture, salinity in irrigation waters is commonly expressed in terms of EC (dS m^{-1}). EC values range from 0.6 for fresh water to 1.5–3.0 for brackish water to about 45 dS m^{-1} in sea water (Maas 1990; Hillel 2000). In India, saline water are defined as water having EC > 2 dS m^{-1} (Minhas 1996; Bajwa and Choudhary 1996). For salinity appraisal of the soils, EC of the saturated extract (ECe) is generally used. An ECe of 4 dS m^{-1} separates a saline soil from a non saline one.

Irrigation with sodic waters leads to increase in sodicity and sodium saturation in soils. The increase in exchangeable sodium percentage (ESP) adversely affects soil physical properties including water infiltration and soil aeration. Under the monsoonal climate, the sodicity development upon irrigation with sodic waters depends upon equilibrium between precipitation of calcite and other salts during irrigation to crops especially in winter season crops and their dissolution with rain water. Thereby, the sodicity (ESP) build up could be adequately predicted (Minhas and Sharma 2006) based upon the annual quantities of sodic waters applied (D_{iw}), the rainfall (D_{rw}) at the site and the evapo-transpiration demands of the crops grown in sequence as $ESP = (D_{iw}/D_{rw})\ (\sqrt{(1+ D_{rw}/ET)}\ (adj.R_{Na})$. Thus based upon the ion chemistry of water (R_{Na}), the parameters like D_{iw}, D_{rw} and ET of crops and their sodicity tolerance, cropping patterns can be appropriately adjusted.

Sodic irrigation water has SAR higher than 10 and RSC higher than 2.5 $mmol_c$ L^{-1} (Minhas and Gupta 1992). However these values are only guidelines since specific values will depend upon the crop, soil chemical and physical characteristics and climate. The sodicity of soil is characterized by the exchangeable sodium percentage (ESP). An ESP of 15 or more separates a sodic soil from a non-sodic soil. The ESP and SAR are related to one another and for most practical purposes are numerically equivalent in the range of 3 to 30 (US Salinity Laboratory Staff 1954).

Waters that are generally classified as unsuitable for irrigation (Ayers and Westcot 1985) might be used safely depending upon the salinity and composition of the water, soil characteristics and management strategies adopted (Ayers and Westcot 1985; Minhas and Gupta 1992; Bajwa et al.; 1998; Tyagi and Sharma 2000; Minhas and Bajwa 2001; Qadir et al. 2003; Grattan and Oster 2003; Choudhary et al. 2004). This has led to replacement of conservative water quality

Table 1 Guidelines for using poor quality irrigation waters

A. Saline water (RSC < 2.5 mmolc L^{-1})

Soil texture (% Clay)	Crop tolerance	Upper limits of EC (dS/m) in rainfall regions (mm)		
		<350	350–550	550–750
Fine (>30)	Sensitive	1.0	1.0	1.5
	Semi-tolerant	1.5	2.0	3.0
	Tolerant	2.0	3.0	4.5
Moderately fine (20–30)	Sensitive	1.5	2.0	2.5
	Semi-tolerant	2.0	3.0	4.5
	Tolerant	4.0	6.0	8.0
Moderately coarse (10–20)	Sensitive	2.0	2.5	3.0
	Semi-tolerant	4.0	6.0	8.0
	Tolerant	6.0	8.0	10.0
Coarse (<10)	Sensitive	–	3.0	3.0
	Semi-tolerant	6.0	7.5	9.0
	Tolerant	8.0	10.0	12.5

B. Sodic waters containing RSC > 2.5 mmolc L^{-1} and EC < 4.0 dS/m)

	Limits of		
Soil texture (% Clay)	SAR $(mmol/L)^{1/2}$	RSC ($mmol_c$ L^{-1})	Remarks
Fine (>30)	10	2.5–3.5	(1) When the waters have Na < 75% (Ca + Mg > 25%) or rainfall is > 550 mm, use the upper limits of the RSC
Moderately Fine (20–30)	10	3.5–5.0	range
Moderately coarse (10–20)	15	5.0–7.5	
Coarse (<10)	20	7.5–10.0	

Source: Minhas and Gupta, 1992

(i) Textural criteria should be applicable for all soil layers down to at least 1.5 m depth.

(ii) In areas where ground water table reaches within 1.5 m, at any time of the year or a hard subsoil layer is present in the root zone, the limits of next finer textural class should be used.

standards with site specific guidelines, where factors like soil texture, rainfall, subsurface drainage, and crop tolerance have been given due consideration (Minhas and Gupta 1992; Table 1). Effective use of saline and sodic waters requires information on the soil-crop-drainage-irrigation management system to maintain salinity and sodicity within permissible limits.

2.1 Consequences of Salinity and Sodicity

Plant growth is affected adversely with saline irrigation primarily through the impacts of excessive salts lowering the osmotic potential of the soil solution (osmotic effects). Excessive concentration and absorption of individual ions e.g. Na, Cl, B etc. may prove toxic and cause specific injury to plants (specific ion effects) and/or retard the absorption of other essential plant nutrients. The reduced water availability at high salinity thus causes water deficits for plants and the plant growth gets inhibited when soil solution concentration reaches a critical concentration value often referred to as threshold salinity. Under the field situations, the first reaction of plants to the use of saline waters is reduction in the germination but the most conspicuous effect is the growth retardation of crops. A general conclusion can be that the detrimental effects of salinity include reduced initial growth resulting in smaller plants. These smaller plants with lesser leaf area in turn are able to produce lesser assimilates for their conversion to seeds. In other terms, a complementary development of vegetative and reproductive phases is necessary for higher yields as translocation of assimilates once developed may remain unaffected by salinity, provided the environmental factors remain favourable during flowering. It is now evident from long term experiments on saline water use that an interplay of factors like nature and content of soluble salts, soil type, rainfall, water-table conditions, nature of crops grown and the water management practices followed, govern the resultant salinity build up *vis-a-vis* crop performance.

The extent of salinity or sodicity in the soil depends upon EC, SAR and RSC of irrigation water. Accumulation of the salts are dependent upon climatic conditions, water table depth, the crops grown and practices of soil-water management adopted to meet leaching requirements (Minhas and Gupta 1992).

Salt accumulation in the soil depends on to a large extent on soil texture which influences the hydraulic properties of the soil. In soils that contain less than 10% clay, ECe often remains lower than that of the irrigation water. Manchanda et al. (1989) reported that concentration factors, ECe/EC (ratio of ECe to that of the irrigation water) were 0.76, 1.12 and 1.8 for soils having clay contents <10%, 10–20% and >20%, respectively. While working with rice-wheat system, Minhas et al. (2007a) concluded that the ECe/EC ratios were between 1.1 and 1.8 for soils deprived of rainfall simulating drier arid area, where it was almost 1 for soils exposed to rain simulating semi-arid region receiving rainfall. The SAR of the saturation paste extract, (SARe) was between 1.6 and 2.0 times the SAR of the irrigation water and 2.0–2.3 times SAR with and without rainfall. The ESP was also in the higher range (16.2–27.4) in plots sheltered from rainfall than in plots exposed to rain (15.8–23.3) (Minhas et al. 2007a). These results suggest additional irrigation water is needed to meet the leaching requirement in arid areas with low rainfall in order to reduced salt build up in the soil. Whereas under monsoonal climates, rainfall that normally falls during summer months would be sufficient to leach the soil profile to keep salinity at a tolerable level.

Irrigation with sodic waters during the dry season and leaching during the rainy season when coupled with crop-induced calcite dissolution results in a cycle of precipitation and dissolution of calcite that limits sodicity build up in soils (Minhas and Gupta 1992; Bajwa et al. 1998; Choudhary 2003; Minhas et al. 2007a). Under the monsoonal climate, a major build-up of salts and Na in the surface soil layers occurs during irrigation of winter crops with sodic water (Bajwa et al. 1983, Bajwa and Josan 1989a; Bajwa et al. 1992; Josan et al., 1998; Choudhary et al. 2004, Minhas et al. 2007b). A quasi-stable salt balance can be reached within 4–5 years of sustained sodic water irrigation (Minhas and Gupta 1992) while the continual rise in pH and exchangeable sodium percentage (ESP) is very slow (Choudhary et al. 2004, 2006b). However, soil ESP values under saline-sodic water irrigated soils was observed to continue to increase in a 10-year field study while these stabilized under sodic water irrigation after 4 years (Choudhary et al. 2004).

Even after long-term use of sodic waters containing high residual carbonate, subsurface soil layers are unaffected for the most part, due to little leaching of sodium (Fig. 1a). The increase in sodicity (higher ESP) in the rice-wheat system is higher than in the millet-wheat because of increased input of sodic water (Bajwa and Josan 1989b). Data on wheat yields with variable *kharif* crops from the experiments (Bajwa et al. 1983; Bajwa and Josan 1989a, b) suggested that an increase in RSC keeping the SAR in the range of 30–40, decreased the wheat yields, especially

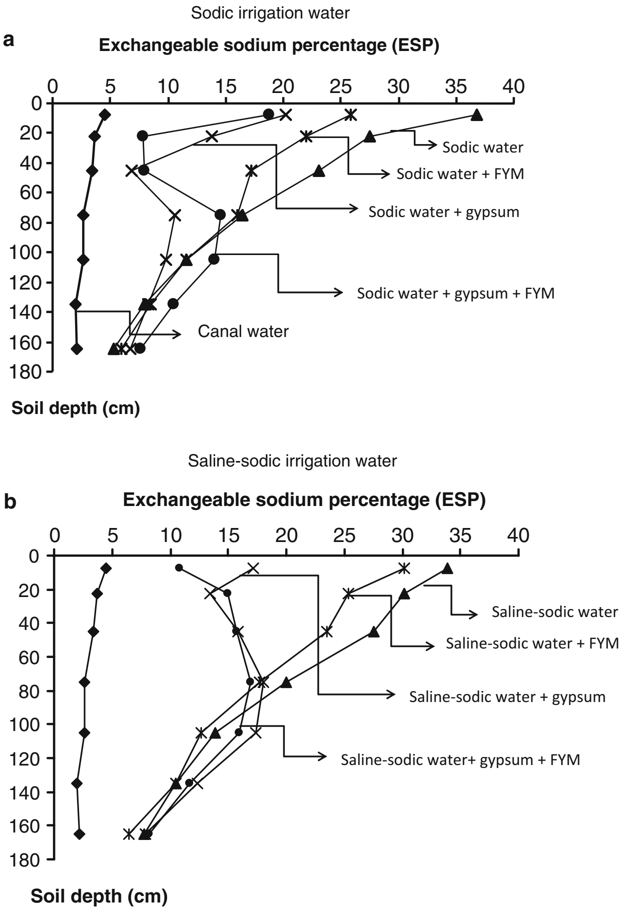

Fig. 1 Depth distribution of exchangeable sodium percentage (0–60 cm) as affected by (**a**) sodic and (**b**) saline-sodic irrigation after 10 years (1989–90 to 1998–99) (FYM-farmyard manure) (Source: Choudhary et al., 2004)

when grown following rice. The decline in wheat yields was not appreciable even with waters having high SAR (25–52) and RSC (>8.0 mmol$_c$ L^{-1}). Thus, it becomes evident that deterioration in soil physical properties and decline in wheat yields with the use of sodic water is higher when rice is grown in rotation. So it is usually feared that rice-wheat system may not be sustainable with the use of sodic waters. However, a critical evaluation of ion chemistry of sodic waters used in most of the micro-plot experiments, Minhas et al. (1996) indicated that proportion of cations, mainly the amounts of calcium in artificially prepared waters were much less than the naturally occurring sodic waters. In addition, attaining desired plant population in rice compared to any other *kharif* crop with sodic waters, higher and uniform salt leaching, availability of canal water to facilitate conjunctive use with sodic water and sufficient rainfall (500–550 mm) besides better economics are some of the reasons that farmers in many semi-arid areas prefer rice-wheat as the most favored cropping system while using naturally occurring sodic waters (Minhas and Bajwa 2001).

Long-term irrigation with saline-sodic water (RSC – 10 mmol$_c$ L^{-1}, SAR – 31.2, EC – 2.90 dS m^{-1}) resulted in higher buildup of Na and soluble salts compared to sodic (RSC- 10 mmol$_c$ L^{-1}, SAR – 19.8, EC – 1.43 dS m^{-1}) water (Choudhary et al. 2004) (Fig. 1). When gypsum was applied at each irrigation to supply 7.5 mmol$_c$ L^{-1} Ca^{2+} to decrease the RSC to 2.5 mmol$_c$ L^{-1}, both under sodic and saline-sodic waters, ESP of the soil decreased (Fig. 1). Application of farmyard manure had a complimentary effect on efficiency of gypsum in reducing ESP of the soil, although it was less efficient than gypsum when applied alone. Due to higher electrolyte concentration, more Na moved to deeper layers and higher values of ESP in soil layers were observed under the saline-sodic water treatment. These trends were similar in presence and absence of applied amendments. In lower soil layers, ESP declined sharply under no amendment treatment and gradually under the amended treatments (Fig. 1).

In cotton-wheat cropping system, Choudhary and Ghuman (2008) observed that the build-up of Na and increase in pH was significantly reduced when one or two canal water irrigation(s) were alternated with irrigation with sodic water. The ESP under high RSC water treatment (RSC – 10 mmol$_c$ L^{-1}, SAR – 14.9) was similar in the 0–15 and 15–30-cm soil layers (30.5). It was relatively higher than that in the 30–60-cm (24.2) layer. The opposite trend, however, was observed when canal water irrigation was alternated with sodic water irrigation and relatively higher ESP values were observed in the lower layers than in the surface layer.

In order to achieve optimum plant growth, adequate physical properties of soils must be maintained by using various combinations of crop, soil and water amendments (Choudhary et al. 2004, 2006a, b; Minhas et al. 2007a, b). The primary concerns are the permeability of soils to air and water movement into and through soils and the ability to prepare seedbeds with a tilth that fosters seed germination and emergence. Adverse effects on crop growth are further supplemented through surface build up of salts (Minhas and Bajwa 2001). Such changes have a direct impact on the activities of plant roots and soil microbes negatively impacting crop growth and yield (Grattan and Grieve 1999a; Mengel and Kirkby 2001).

3 Managing Saline and Sodic Waters

Despite the difficulties associated with use of saline and sodic water for irrigating crops and the potential for reduced soil permeability, the fact remains these can be a valuable resource (Murtaza et al. 2009). Consequently, if the challenges of sustaining global food supplies are met, it is essential that these poor-quality waters are used correctly to sustain crop production.

Two major approaches can improve and sustain crop productivity in saline and sodic environments. One approach is modifying the environment to suit the plant and the other is modifying the plant to suit the environment. Both these approaches have been used, either individually or in combination, but the former has been used more extensively because it facilitates alternative production inputs. The later is not been that successful at this time because of the complexity of crop salt tolerance and difficulty in developing crops with high salt tolerance (Läuchli and Grattan 2007). It is likely that salt tolerance is controlled by a number of genes. The development of management options requires sensitivity analysis of the parameters affecting crop yield (Zeng et al. 2001). Most of the past research has treated saline–sodic water use in the context of root zone salinity/sodicity management to maintain an environment favorable to crop production (Minhas and Gupta 1992; Bajwa et al. 1998, Choudhary et al. 2006a). This has led to the development of management practices at the field level without considering their implications and practicality at the larger regional (i.e. farm/irrigation-system/river-basin) level. However, in order to sustain agricultural production, a salinity balance has to be maintained at the field and basin levels (Tyagi 2003).

Practical options for safe use of poor quality waters for sustainable crop production should aim at improving physical and chemical properties for soils receiving saline and/or sodic waters and controlling buildup of salinity/sodicity in the soil. Such an approach will not only add an additional water source in arid and semi-arid areas, but also can minimize the rising water table problem at the same time.

Management strategies to sustain productivity using saline and sodic waters include crop selection, irrigation management strategies, chemical/organic amendements and fertility management. No single management practice is able to control salinity and sodicity of irrigated soils in itself but rather a combination of practices are required. Each management option is described separately for better understanding in the following sections.

3.1 Salt Tolerance and Crop Selection

Crops differ considerably in their ability to tolerate salinity/sodicity. These crop-specific differences can be exploited for selecting crops that can produce satisfactory yield under given level of root zone salinity and sodicity (Minhas and Gupta 1992; Choudhary et al. 1996a, b; Koyoma et al. 2001). General guidelines have been given for selection of crops based on their relative tolerance to salinity (Maas and Grattan 1999) and sodicity (Gupta and Abrol 1990). Crops requiring less water over the season such as oilseeds can tolerate high levels of salinity/sodicity in the irrigation water. Most of the pulses and vegetables are sensitive to salinity. Cotton, on the other hand, is a salt tolerant crop but it is sensitive during crop emergence. The successful use of saline/sodic waters generally requires crops that are semi-tolerant to tolerant to these abiotic stresses (such as mustard, wheat, cotton). In addition, crops with low irrigation water requirements should also be selected whereas crops like rice, sugarcane and forages that are salt sensitive or require large quantities should be avoided (Minhas and Bajwa 2001; Choudhary 2003). The changes in tolerance to osmotic stress can also occur due to several factors such as ageing and presence of other toxic constituents along with salinity (Minhas et al. 1996: Katerji et al. 2000).

Minhas and Gupta (1992) compared the tolerance of wheat from experimental results under two conditions; (i) sodic soils undergoing reclamation and (ii) soils ESP increasing when irrigated with sodic waters. Lower plant tolerance was observed under the latter condition. The differential availability of Ca^{2+} seemed to play an important role as during reclamation of alkali soils. Calcium furnished by gypsum to reduce soil ESP also provided a source of calcium for the crop whereas in soils having their ESP increased, calcium concentrations declined, and therefore was less available to the crop, due to its precipitation as calcite.

Apart from variations of different crops to tolerate salinity/sodicity, crop cultivars also vary widely in salt tolerance. Usually, there is a negative correlation between tolerance of cultivars and their potential yields but it is not always the case. Cultivars having high yield potential continue to be viable and should be the preferred choice even under saline environments (Minhas and Gupta 1992). Typical example is that of very popular and high yielding wheat cultivar 'PBW 343' grown in northwest India can be grown with irrigation waters having RSC up to 6.5 $mmol_c$ L^{-1} without any substantial loss in grain yield (Choudhary et al. 2007). While screening large number of triticale line in soils irrigated with high RSC waters, two groups of lines performed better. One group of high yielders under non-stressed conditions recorded higher yields than other lines at higher RSC levels in absolute terms despite having lower relative yield. Other group, on the other hand, showed higher relative tolerance and yielded progressively higher at higher RSC levels than at no or low RSC levels (Choudhary et al. 2003).

Sodicity also affects crop nutrition. Crop varieties having higher tolerance have also been able to maintain low Na/K ratio in shoots by restricting Na uptake (Gill and Qadir 1998). Tolerance of a cultivar to irrigation with sodic waters ($EC<2$ dS m^{-1}, $RSC>5.0$ $mmol_c$ L^{-1}) also depends upon ability of the plants to exclude Na and absorb nutritionally adequate amounts of Ca (Choudhary et al. 1996b). Wheat and barley cultivars possessing penetrative root systems and capable of producing higher number of spikes per unit area with bolder grains could produce high yields even at an ESP of 40–50 in 0–30 cm soil developed due to long-term irrigation with sodic waters (Choudhary et al. 1996a, b).

Investigations using three cotton cultivars under long-term irrigation with sodic waters having RSC (5 to15 $mmol_c$ L^{-1}) increased the ESP by16–56 (0–30 cm soil) as compared to plots irrigated with canal water. Seed-cotton yield under ESP of 56 was 69% for the tolerant cultivar (F-846) and 29% for the sensitive cultivar (F-505) relative to the plants irrigated with non-sodic canal water (Choudhary et al. 2001). The tolerant cultivar produced heavier bolls than did the other two cultivars in the highly sodic environment. High RSC waters adversely affected fiber quality (2.5% span length, micronaire value and bundle strength) in the sensitive cultivar at an ESP of 56 but not in the tolerant cultivar.

For sugarcane crop, a cultivar tolerant to salinity possessed a higher number of millable canes and a larger single cane weight resulting in higher cane yield in a saline water-irrigated soil (EC 3.5 –4.0 dS m^{-1}), for both planted and ratoon crops, compared to sensitive cane cultivars (Kuldeep-Singh et al. 2007). In terms of juice quality, the tolerant cultivar was able to maintain higher °brix and sucrose content resulting in higher commercial cane sugar and sugar recovery in a saline stressed environment. Salinity has been found to improve crop quality in a number of other cases (Maas and Grattan 1999). However there are cases where salinity reduces crop quality as well.

Plant biotechnology approaches with the aim of producing transgenic crops with enhanced salt tolerance and performance under field conditions is a very attractive approach to sustaining crop production under saline and sodic environments. To date, success stories are very limited (Wani 2009). Assuming genetic engineering for production of salt tolerance is successful, these transgenic crops could provide us with tolerant crops that show superior productivity on salt-affected soils in comparison with existing varieties and cultivars.

3.2 Use of Amendments

3.2.1 Chemical Amendments

The adverse effects of irrigation with sodic water on physico-chemical properties of soils can be mitigated by the application of amendments that liberate free Ca^{2+}. These can etiher be amendments containing Ca such as gypsum or acidifying material to dissolve calcite. The need for gypsum application for ameliorating the sodicity effects occurring due to irrigation with high RSC-SAR waters is of the recurring nature. Application of gypsum has earlier been recommended when RSC of the irrigation water exceeded 2.5 $mmol_c\ L^{-1}$ (Bhumbla and Abrol 1972). However, later researches have shown that factors such as the level of the deterioration of the soil, cropping intensity and the water requirements of the crops will ultimately decide the amount of gypsum required. Sharma et al. (2001) evaluated the sustainable yield index (SYI), which indicates that minimum yield as a fraction of the maximum observed yield. Graded doses of gypsum varying from 12.5% to 100% of gypsum requirement were applied to evaluate its impact on sustainability of rice and wheat yields in sodic water irrigated soils. Sustainable yield index varied from 0.57 to 0.65 in rice and from 0.54 to 0.65 in wheat (Table 2).

Table 2 Crop yield and sustainable yield index (SYI[a]) for rice and wheat as affected by rate of gypsum application under sodic water irrigation

Treatments	Gypsum applied	Crop yield (Mg ha^{-1})		Sustainable yield index (SYI)	
(% GR[b])	(Mg ha^{-1})	Rice	Wheat	Rice	Wheat
0	0	4.01	3.55	0.57	0.54
12.5	1.25	4.22	3.75	0.60	0.60
25.0	2.50	4.13	3.68	0.60	0.58
50.0	5.00	4.26	3.82	0.61	0.62
75.0	7.50	4.22	3.83	0.62	0.62
100.0	10.00	4.48	3.94	0.62	0.63
Canal water	Nil	4.46	3.85	0.65	0.65
LSD ($p = 0.05$)		0.24	0.16		

[a] $SYI = (Y - S)/Y_{max}$, where *Y* average yield, *S* standard deviation, Y_{max} the maximum yield in the study area (6 Mg ha^{-1} for rice and 5 Mg ha^{-1} for wheat)

[b] *GR* Gypsum requirement (Source: Sharma et al., 2001)

Sustainable yields of crops in rice-wheat system, irrigated with sodic water are possible with occasional application of gypsum and farmyard manure (Minhas and Bajwa 2001). Among *rabi* crops, response of mustard to gypsum was more than wheat and barley. Gypsum in order to supply 2.5 and 5.0 mmol$_c$ L^{-1} to sodic irrigation water for wheat and rice, respectively, was sufficient for maintenance of higher yields (Bajwa and Josan 1989a). Once the role of gypsum is established for sustaining crop production with the use of sodic waters, questions regarding its mode, amount and time of application have to be answered. Bajwa et al. (1983) observed that gypsum applied at each irrigation was more effective in increasing maize yields in maize-wheat sequence irrigated with water having RSC of 8 mmol$_c$ L^{-1} as compared to its single dose applied annually. For rice-wheat system irrigated with water of RSC 6.8 mmol$_c$ L^{-1}, response to gypsum either applied as one dose or at each irrigation was the same (Bajwa and Josan 1989a). With higher RSC water (10.3 mmol$_c$ L^{-1}), while the improvement in wheat yield was similar for two modes of gypsum application, rice responded better to gypsum when it was applied with each irrigation. It occurred because more water was applied to rice leading to appreciable increase in soil sodicity during the seasons affecting rice yields. In case of wheat, depth of irrigation water applied being smaller, increase in soil sodium saturation was not sufficient to adversely affect its yields. Comparing the time of application of gypsum, Yadav and Kumar (1994) observed that its application before the onset of monsoons (rainy season) was better than its application before pre-sowing irrigation of *rabi* crops and at each irrigation. Pyrites has also been used for amending the deleterious effects of high RSC waters. Chauhan et al. (1986) observed that pyrite application before the sowing of wheat crop has proved better than its split application at each irrigation or mixing it with irrigation water. More reaction time and better oxidation of pyrite resulted in more reduction in pH and soil sodium saturation when it was applied before sowing.

3.2.2 Gypsum Beds

The high cost on gypsum demands its efficient utilization. The use of gypsum beds technique (Pal and Poonia 1979) improves its solubility and application efficiency. Such a practice will also reduce the costs involved in powdering, bagging and proper storage of the material before its actual use. The gypsum bed is constructed with brick-cement-concrete, the size of which depends primarily on the discharge of sodic well water. A net of iron bars covered with wire net (2 mm × 2 mm) is fitted at the height of 10–20 cm from the bottom of the bed floor and this supports a bed of gypsum clods. Well water then passes through the gypsum bed before exiting into the irrigation channel (Pal and Poonia 1979). The dissolution of gypsum is affected by factors such as size distribution of gypsum fragments, the flow rate, the salt content and chemical composition of water (Kemper et al. 1975; Singh et al. 1986). The calcium picked up by the passing well waters depends upon the contact time and surface area of the gypsum clods. Typical increases range from 3 to 5 $\mathrm{mmol_c\ L^{-1}}$ but seldom exceed 8 $\mathrm{mmol_c\ L^{-1}}$ (Singh et al. 1986). Usually the height of gypsum bed recommended to bring RSC within permissible limits is 30–60 cm.

3.2.3 Organic Materials

Farmyard manure and other organic materials have not only the nutritive value, but play an important role in structural improvements, which further influences leaching of salts and reduce their accumulation in the root zone. The other advantages of these materials in saline water irrigated soils are in terms of reducing the volatilisation losses and enhancing nitrogen-use efficiency and the retention of nutrients in organic forms for longer periods also guards against their leaching and other losses. Therefore, the addition of farmyard manure and other organic/green manure should be made to the maximum possible extent.

Organic materials can improve sodic soil conditions through mobilization of Ca^{2+} from $CaCO_3$ and hasten the reclamation process. Choudhary et al. (2006a) conclusively found that with mobilization of Ca^{2+} from $CaCO_3$ during decomposition of organic materials such as farmyard manure, green manuring (*Sesbania aculeata*), the need of gypsum required for controlling the harmful effects of sodic water irrigation can be reduced or eliminated while sustaining the yields of rice and wheat grown in calcareous soils. The application of crop residues such as wheat straw before rice transplanting, although was less effective than farmyard manure and green manuring in increasing rice yield over the unamended sodic water treatment but was at par with green manuring in its residual effect on following wheat yield.

In sugarcane crop, farmyard manure was observed to be more effective under saline-sodic (38% increase) than under sodic water irrigation (23% increase) (Choudhary et al. 2004). However, the combined effects of gypsum and manure applied together were beneficial only under sodic water irrigation. Relative to canal water irrigation treatment, there was no decline in yield up to an ESP of 12 beyond which a significant reduction in cane yield occurred. An ESP of 10–12 can be maintained under long-term sodic water irrigation through combined application of gypsum and manure. In case of saline-sodic irrigation, sugar yield under farmyard manure treatment (10.8 Mg ha^{-1}) was equivalent to that under the gypsum plus manure treatment but was significantly higher than under the gypsum treatment (9.0 Mg ha^{-1}). This suggests that cane and sugar yields with good quality juice can be sustained by applying gypsum/farmyard manure or both under sodic and only farmyard manure under saline-sodic water irrigation.

3.3 Fertilizer Management

The relations between salinity and mineral nutrition of plants are extremely complex and it is no easy task to reconcile results from salinity-nutrition experiments conducted in the field vs. the greenhouse; in soils vs. solution cultures; using single salts vs. mixed salts; under one set of environmental conditions vs. another set; or studies conducted over the short-term vs. the long-term. Nevertheless by accounting for these differences in experimental parameters, one can begin to see more consistencies in salinity-nutrient interactions and obtain a better understanding of the overall salinity-nutrient relations in plants (Grattan and Grieve 1999b).

Plant performance, usually expressed as a crop yield or plant biomass, may be adversely affected by salinity-induced nutritional disorders. In the field, additions of nutrients have increased the growth of both glycophytes and halophytes, provided that the plants were not experiencing severe salt stress. Relief of the growth-limiting stress, salinity or nutrient deficiency, promotes growth more than relief of the next limiting factor. Therefore, addition of a limiting nutrient may increase, decrease or have no effect on crop/plant performance, depending on the severity of salinity stress. Consequently, interpretation of plant salt tolerance expressed on a relative basis under variable soil fertility can be misleading.

Salinity-induced nutritional disorders may develop on plants from the effect of salinity on nutrient availability, competitive uptake, transport or partitioning within the plant. For example salinity reduces phosphate uptake and accumulation in crops grown in soils primarily by reducing phosphate availability; whereas in solution cultures reductions may be due to a competitive process. Salinity dominated by Na^+ salts not only reduces Ca^{2+} availability but reduces its transport and mobility to growing regions of the plant, thereby affecting the quality of both vegetative and reproductive organs (Choudhary et al. 1996b, 2001). These disorders are aggravated when transpirational demands are high. Salinity can directly affect nutrient uptake as has been observed in the reduction in K^+ uptake by Na^+ or NO_3^- uptake by Cl^-. The occurrence of these disorders ultimately affects crop yield or quality that depends upon the plant species and the experimental conditions where the study was conducted.

Salinity can cause a combination of complex interactions affecting plant metabolism or susceptibility to injury. In several studies it has been shown that salinity increases the internal requirement for a particular nutrient. Examples were given for

N in the halophyte *Spartina alterniflora,* P in tomato, and K^+ in spinach. In other studies, it was shown that salinity can cause plants that are deficient in an element to have a lower cellular tolerance for a specific ion. Moreover there are undoubtedly a multitude of other interactions yet to be found.

Despite a large number of studies that demonstrate that salinity reduces nutrient uptake and accumulation or affects nutrient partitioning within the plant, little evidence exists that adding nutrients at levels above what is considered optimal in non-saline environments improves plant growth or crop yield in saline environments. Swarup and Yaduvanshi (2004) observed that applying additional quantities of fertilizer N to overcome adverse effects of high salinity may not pay off well when the salinity is a growth limiting factor. Nutrient additions, on the other hand, have been more successful in improving crop quality. For example Ca^{2+} additions to soils or as foliar sprays can sometimes correct disorders caused by Na-induced Ca^{2+} deficiency.

Nutrient additions may also reduce the incidence of injury. An adequate supply of Ca^{2+} maintains membrane integrity and selectivity thereby reducing Na^+ and Cl^- toxicity in tree and vine crops. Benefits from added Ca^{2+} are usually observed in solution culture studies when NaCl is the sole salinizing agent. There are also studies that have shown that increased concentrations of NO_3^- can reduce Cl^- toxicity in certain tree crops. While these studies may have practical implications, there is a danger that this practice may increase NO_3^- concentrations in the groundwater (Grattan and Grieve 1999a, b). Chloride also reduces the availability of soil P to plants. Therefore, soils irrigated with Cl^- rich waters respond to higher amounts of P fertilizers. Phosphorus can also help mitigate the adverse effects of Cl^- in crops (Manchanda et al. 1982). For soils irrigated with SO_4^{2-} rich waters, P levels recommended for normal non-saline soils are sufficient.

It is reasonable to believe that numerous salinity - nutrient interactions are occurring at the same time but whether they ultimately affect crop yield or quality depends upon the salinity level and composition of salts, the crop species, the nutrient in question and a number of environmental factors.

3.4 Irrigation Management

3.4.1 Leaching Requirement for Maintaining Root Zone Salinity

Salts accumulate in the root-zone of plants with each saline water irrigation and reach detrimental levels causing reduction in crop yields if leaching does not take place. The properly designed surface irrigation methods can maintain favorable salt and water regime in the root-zone.

Leaching requirement is the minimal fraction of total water applied that must pass through the root zone to prevent the reductions in crop yields below the acceptable level. This concept is of particular importance for the situations of no or little rainfall where nearly the steady state conditions can be achieved. Field studies conducted in Imperial and San Joaquin valley of California demonstrated that saline waters (EC 4–9 dS m^{-1}) can be used for achieving acceptable yields of salt tolerant crops such as sugar beet, cotton and sugarcane provided some leaching is facilitated through pre-plant irrigation with fresh water (Rhoades 1999; Pitman and Läuchli 2002). Feasibility of crop irrigation with saline water, however, needs to be evaluated on long-term basis for each crop species with allowance of leaching of soil between cropping seasons to control soil salinity (Goyal et al. 1999a, b).

In continental monsoon climate, concentration of rains in a short span of 2–3 months is the most uncontrolled factor causing non-steady state conditions. Under such situations, salt tolerance at critical stages of crop change with patterns of salinization and initial distribution of salinity in soils (Minhas and Gupta 1993). International Water Management Institute (IWMI) studies in Pakistan have also shown that rather than having one specific threshold value for salt tolerance, crops react differently depending upon the time of imposed salinity. Irrigation water consumed by evapo-transpiration leaves the remaining soil water more concentrated with salts. The leaching requirement increases with salinity of the irrigation water and the sensitivity of the crop for salinity (Kijne 2003).

A general recommendation is the application of excessive water to meet the leaching requirement and maintain a desirable salt balance in the soil having adequate drainage. In drier arid areas with low rainfall, 15–20% more water for each irrigation should be applied while crops are irrigated with saline water to promote leaching as compared to good quality water. This may not be the case in areas with monsoon type climate (Minhas and Gupta 1992; Minhas 1996). While using saline-sodic water ($EC_w = 3.2$ dS m^{-1}, SAR=21, and RSC≥4 $mmol_c$ L^{-1}), about, 30–50% higher salinity build up even in light textured soil was observed when 50% extra water was applied to meet the leaching requirement in rice-wheat and maize-wheat systems in monsoonal South Asia (Bajwa et al. 1983; Bajwa and Josan 1989a). The general strategy to use more efficiently the monsoon rainwater for leaching and reduce the salt build up in the root zone soil seems to be more useful in areas receiving more than 400 mm rainfall. However, in the event of sub-normal rainfall year, a heavy pre-sowing irrigation with good quality water should be applied so that the accumulated salts during the preceding *rabi* season are pushed beyond the root zone (Minhas and Gupta 1992).

3.5 Conjunctive Use of Poor and Good Quality Waters

In arid and semi-arid regions, canal water supplies are most often not assured or in short supply such that farmers are forced to use saline/sodic waters to meet the crop water requirements. Available options to practice conjunctive use of salty and fresh water are blending or using them separately in cyclic mode. Different quality waters can be blended in the supply network making tailor-made water available for each crop and all soil conditions. Blending is promising in areas where freshwater supplies can be made available on demand. The potential of blending two different water supplies depends on the crops to be grown, salinities/sodicities and quantity of fresh water supplies and economically acceptable yield reductions (Minhas and Gupta 1992).

Allocation of the two waters separately, if available on demand, can be done to different fields, seasons or crop growth stages so that salinity/sodicity stresses are minimized during sensitive growth stages in the crop. Therefore, the cyclic use of multi-quality waters can be made inter- or intra-seasonal (Minhas et al. 2007b). Cyclic use is more common and offers several advantages over blending as better quality water can be used for pre-sowing and early stages of crop growth and then switching to saline water later on when the already established crop is able to tolerate relatively higher salinity levels (Minhas and Gupta 1993). Rhoades et al. (1992) have advocated the seasonal cyclic use, called 'Dual Rotation' strategy where non-saline water is used for salt/sensitive crops/initial stages of tolerant crops to leach out the accumulated salts from irrigation with salty waters to previously grown tolerant crops. This strategy may work better in arid climate with very low rainfall but it is of natural occurrence in the monsoonal climate. Here the salt accumulations mainly occur with saline irrigation to winter crops while the added salts get leached with concentration of rainfall (July-September) during summer season crops. Rhoades (1999) proposed that blending low salinity water with high salinity waters can result in loss of consumable water, particularly for salt-sensitive or moderately salt sensitive crops. Moreover, crop production can be optimized from the same total water supply if the two water sources are used sequentially rather than blending the two. At the same level of weighted average salinity of the irrigation water, the yields of different cyclic modes were higher than the estimated yields from mixing the two (Minhas and Gupta 1992; Sharma and Minhas 2005).

In case of irrigation water having high residual alkalinity, the strategy that would either minimize the precipitation of calcium carbonate or maximize the dissolution of precipitated calcium would be the best choice (Bajwa and Josan 1989c; Minhas and Bajwa 2001). Blending of surface waters with high RSC ground water usually in equilibrium with naturally occurring calcite, should result in under-saturation with respect to calcite. Consequently, application of blended water or application of higher quality waters in cyclic mode should have a tendency to pick up calcium through dissolution of native calcite. Minhas et al. (2007b) evaluated the sustainability yield index of rice and wheat when sodic and good quality waters were used either by blending or by their alternate inter- or intra seasonal use. The sustainability yield index (SYI) is the minimum guaranteed yield as referenced to the maximum observed yield (Y_{max}) with good quality water was calculated as $SYI=(Y-S)/Y_{max}$ where'Y' is the average yield and 'S' the standard deviation. The SYI ranged between 0.52 and 0.75 and 0.79–0.95 for rice and wheat, respectively. Marginal improvements in the yield index with cyclic uses over blending indicate a higher sustainability with the former. Furthermore, blending requires the creation of additional facilities for blending the two water supplies. When sodic and good quality waters were rotated inter-seasonally, the dilution effects of monsoonal rains in NW India helped to optimize greater use of sodic water for rice compared to wheat (Minhas et al. 2007b).

Alternating irrigations with good quality and sodic waters maintained the ESP at relatively lower levels, maintained reasonably good soil physical-condition of soil and helped in sustaining adequate crop yields (Bajwa and Josan 1989c; Choudhary et al. 2006b; Choudhary and Ghuman 2008). Perusal of data in Table 3 shows that when irrigated with sodic water, yields of wheat grown following rice were lower than when grown after cotton crop. Field observations further suggest that farmers with some access to canal water supplies are able to sustain the yields of rice and wheat whereas yield of these crops declined on farmers' fields that did not have access to such waters (Minhas et al. 1996). However, in such situations particularly in arid climate, canal water supplies may not always be available at the time of sowing and the farmers are left with no alternative except to use sodic ground water for irrigation to avoid delay in sowing. This can have devastating effects on cotton stand establishment. Therefore, the long-term effects of sodic water applied as the first (pre-sowing) irrigation in cyclic modes were investigated in cotton based cropping systems (Choudhary and Ghuman 2008; Choudhary et al. 2006b).

Choudhary and Ghuman (2008) observed a greater decline in seed-cotton yield (16.5% year^{-1}) than that in wheat yield (5.9% year^{-1}) when irrigated with sodic water (SW, RSC 10.1 $\text{mmol}_c\ \text{L}^{-1}$, SAR 14.9, EC 1.4 dS m^{-1}). Higher crop yields were observed when the irrigation started with canal water (CW) and involved only one irrigation with sodic water in a cycle (2CW:SW, CW:SW). The yields were also higher in an irrigation cycle starting with sodic water but followed by 2 irrigation with canal water (SW:2CW). However, when irrigation was initiated with sodic water involving only one irrigation with canal water in a cycle (SW:CW, 2SW:CW), the decline in seed-cotton yield was relatively greater (18–23%) than that in wheat yield (10%). This suggests that in a cyclic strategy involving sodic water, pre-sowing irrigation of cotton should be performed with good-quality canal water to ensure higher yields. However, if canal water is not available at the time of planting cotton crop, sustainable seed-cotton yields can also be achieved even with pre-sowing irrigation with sodic water, provided the deterioration in soil properties is prevented ($\text{ESP} \leq 10$ in the root zone) by applying CW irrigation later (Table 3).

Winter crops like wheat and sunflower can be grown reasonably well even with pre-sowing irrigation using sodic water. These crops responded to the total proportion

Table 3 Effect of cyclic use of sodic and canal water on crop yields (Mg ha^{-1}) under various crops and cropping systems

	Rice–wheat[a]		Cotton–wheat[b]		Cotton–Sunflower[b]
IrrigationTreatments	Rice	Wheat	Cotton	Wheat	Sunflower
Canal water (CW)	6.78	5.43	1.32	5.20	3.28
Sodic water (SW)[c]	4.17	3.08	0.95	4.43	2.55
2CW:SW[d]	6.67	5.22	1.26	5.10	2.99
CW:SW	6.30	5.72	1.21	4.95	2.88
CW:2SW	5.72	4.85	1.15	4.70	2.67
SW:2CW			1.22	4.82	3.01
SW:CW			1.08	4.70	2.80
2SW:CW			1.02	4.75	2.69
LSD ($p = 0.05$)	0.60	0.50	0.18	0.21	0.22

[a] 1981–1985;

[b] 1996–2002;

[c] $\text{RSC} > 5\ \text{mmol}_c\ \text{L}^{-1}$

[d] Cyclic use of two irrigations with canal water followed by one with sodic water

(*Source*: Bajwa and Josan, 1989c; Choudhary et al. 2006b; Choudhary and Ghuman, 2008) of sodic water applied rather than the order of sodic water and canal water used in a cyclic strategy (Choudhary et al. 2006b; Choudhary and Ghuman 2008) (Table 3). These results are of considerable agronomic significance when canal water supplies progressively decrease from the head reach to the tail reach in a canal command (Tyagi 2003) and are not available at the time of sowing of a crop. The water deficiencies coupled with decreasing water quality from head to tail reaches calls for spatial re-allocation of canal water to facilitate pre-irrigation and conjunctive use options using good quality canal water. It will help sustain crop productivity and raise the farm income of the beleaguered farmers at the tail end in most of the arid regions. Furthermore, occasional application of farmyard manure and gypsum in combination with alternate irrigation with saline-sodic ($SAR > 10$, $RSC > 2.5\ mmol_c\ L^{-1}$) and fresh water in cyclic manner could effectively reclaim saline-sodic soils following rice–wheat crop rotation (Murtaza et al. 2009). The proposed strategy offers the additional advantage of integrated water resources management by using low quality water for soil reclamation while saving better-quality water for producing high-value crops.

Higher proportions of sodic water used in blending/cycle can also degrade the quality of the harvested product. Examples include a reduction in potato grade and weight loss during storage as well as the smaller seeds and lower oil content in the case of sunflower (Chauhan et al. 2007).

3.6 Irrigation Intervals

A general recommendation under saline and sodic soil conditions is to apply light and frequent irrigations to overcome the adverse effects of soluble salts on plants and poor hydraulic properties on soils. Sharma (2008) reported that frequent yet light irrigations of saline water are beneficial in that these would minimize the quantities of total water and salts applied. However, under arid conditions, higher transpiration rates from wetter soils kept closer to field capacity due to frequent, saline irrigations may lead to increased salinity in the soil solution (1.5–2.0 folds), thereby taking away the benefits of higher irrigation frequency (Minhas 1996; Bajwa et al. 1998; Choudhary 2003).

In a long-term study, Bajwa et al. (1993) reported that crop responses to shorter irrigation intervals under involving sodic and saline-sodic waters depended upon the season in which crop was grown (through moderating soil temperature) and its relative salt and Na tolerance.

3.7 Method of Irrigation

The distribution of water and salts vary with the method of irrigation. The method adopted should create and maintain favorable salt and water regimes in the root zone so that water is readily available to plants without affecting growth and yield. Surface irrigation methods such as border strips, check basins and furrow are the oldest and most commonly practiced in India. For saline water irrigated soils, the furrow irrigation and bed planting system was better than conventional planting in cotton-wheat and pearl millet-wheat rotations (Sharma 2008). Adoption of measures for better intake of rainwater (tillage to open up soil) and its conservation in soil via checking unproductive evaporation losses (soil/straw mulching) is recommended during monsoon season

Surface irrigation methods generally result in excessive irrigation and non-uniformity in water application. Consequently the on-farm irrigation efficiency is low (60–70%). High energy pressurized irrigation methods such as sprinkler and drip are typically more efficient as the quantity of water to be applied can be adequately controlled, unlike surface irrigation systems. Sprinklers help distribute water uniformly even on undulating soils and those with variable infiltration rates due to soil type variability. Sprinklers also increase the efficiency of salt leaching (Minhas and Gupta 1992). Saline water use through sprinklers, however, may cause leaf burn due to accumulation of toxic quantities of salt. This is particularly true for sensitive crops that exhibit high rates of foliar salt absorption during periods of high evaporative demand. Water use efficiency, although decreased with salinity, was higher when applied by using the sprinkler than by surface.

Drip irrigation has revolutionized the production of some high value crops and orchards in countries like Israel using saline water. Because regular and frequent water applications are possible with drip irrigation, crops have performed better using this system as opposed to others because a lower soil-water salinity is maintained near the drip emitter where root density is high (Kahlon et al. 2004; Rajak et al. 2006). Hence the drip system seems to be the best method for irrigation using saline/sodic waters because it avoids leaf wetting and injury to plants and maintains optimum conditions for water uptake by roots. Drip irrigated crops have also been found to show higher water uptake by their roots resulting in higher water use efficiency and yield of vegetables. Recently while using waters having high residual alkalinity for irrigating tomatoes, Choudhary et al. (2010) reported superiority of drip over furrow irrigation in terms of yield, size and quality of fruits.

Drip irrigation has some disadvantages too. For example clogging of drippers can occur due to salt precipitation. This requires periodic acidification of the irrigation water. In addition, not much advantage of drip irrigation was observed for crops grown during hot summers having high evaporative demands with excessive loss of water from the wetted surface. Accumulated salts cause difficulties in the planting of subsequent crops because leaching of salts are often required using flood or sprinkler irrigation.

4 Social Aspects and Cost of Sustaining Irrigation with Saline and Sodic Waters

Several water quality issues pose similar challenges to water resource managers. Agricultural drainage water containing salts and other constituents must be disposed, reused, evaporated in ways that support irrigated agriculture without harming the environment. In many areas, the salts in drainage water by one region degrade the quality of water downstream. Such problems can occur within or between political jurisdictions. The problem caused by selenium in drainage water in California pertain largely to that state, while the salt load in drainage water from Arizona's Welton-Mohawk district degrades water quality in California and Mexico. Public officials have been working for many years on irrigation and drainage issues that involve interaction among farmers, districts, and states.

The main question 'Is irrigation sustainable'. The answer to this question is clear-cut yes, but the society must be 'willing to pay the price' (Clemings 1996). The science and technology of managing saline and sodic waters have been studied for many years. Technology is available to sustain crop production using these waters in most of the arid and semi-arid regions. However, the cost of sustaining crop production will vary among regions and over time with public preferences. This cost will vary according to resource endowments, economic development of a region and social preferences.

In many areas, complex water quality problems must be solved to sustain irrigation over decades and longer. The concentration of naturally occurring elements (selenium, arsenic and boron) must be reduced in agricultural drainage water to protect the quality of groundwater and surface water. Farmers can reuse drainage water, rather than discharging it to public water ways. Farmers can blend drainage water with fresh water supplies or use it in conjunction with fresh water irrigations (Grattan and Oster 2003). A combination of strategies may be the best solution.

It is reasonable to wonder why so many irrigation schemes are characterized by salinity, water logging and persistent groundwater draft when harmful impact of these problems have been understood for years (van Schilfgaarde 1994). The primary reason is the fundamental disconnect between public or social objectives and farm level goals with regard to irrigation (Knapp 1999). Furthermore, many publicly funded irrigation schemes have been formulated to generate regional economic activity without looking at impacts these can have particularly in the regions having canal network and brackish groundwater.

Irrigation with saline and sodic waters can only be sustainable if salts and drainage water are adequately removed from the underground environment and managed to minimize environmental damage. In Indian Punjab, installation of a large number of shallow tube wells in central parts is causing withdrawals that exceed the recharge rate in that region. With this continued practice, there is danger of deteriorating ground water quality and quantity. In the North Western region of India where in some places salinity coexists with water logging, sub-surface drainage is often required to reclaim the salinized area. In that case, the cost of installing subsurface drainage should be added to the cost of reclamation. Nevertheless, such awareness should help farmers and policy makers decide whether to persist with irrigated agriculture or not. The other possibility is to evaluate the feasibility of saline aquaculture in such areas (Sehgal et al. 2000).

Wichelns and Oster (2006) summarized the future of sustainable irrigation and posed challenges to public officials and researchers in twenty-first century: (1) continue to support yield-enhancing agricultural technologies and methods to mitigate the environmental impacts of irrigated agriculture, (2) continue to reform policies that fail to encourage efficient use of scarce resources, (3) continue to inform public officials about the potential implications of policy decision that influence farm-level strategies, and (4) provide policy recommendations based on good science and a meaningful understanding of farm-level goals, opportunities, and constraints, and of the environmental impacts of irrigation.

5 Conclusion

Saline and sodic ground waters constitute an important resource in water scarce arid and semi-arid regions. Production of more food, feed, energy and fiber for the world's expanding population will depend on further exploitation of these low quality waters in irrigated agriculture. Improper use of poor quality waters can pose grave risks to soil chemical and physical quality and the environment. For safe use of saline and sodic waters on sustainable basis, options include the management of crop/cultivars, irrigation water, chemical and organic amendments, soil fertility management, and need to be considered in an integrated manner. In future, understanding the process of salt tolerance and its improvement through genetic engineering is the most likely means of propagating crop cultivation with these waters. Modifications in canal water deliveries for facilitating presowing irrigation in the afflicted areas have a potential to enhance the use of these low quality waters. Cost of sustaining crop production using these waters will vary among regions according to resource endowments, economic development and social preferences.

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Climate Change Impact on Forestry in India

Geetanjali Kaushik and M.A. Khalid

Abstract Climate change represents a significant threat to global biodiversity and ecosystem integrity. Climate change is expected to have also impacts on forest ecology. It is thus important to make assessments of possible impacts of climate change on forests in different regions to allow respective governments and communities to adapt. Climate change is projected to affect individual organisms, populations, species distributions and ecosystem composition and functions. This impact can be both direct by temperature increases, precipitation and sea level changes, and indirect, for instance by changing the intensity and frequency of wild fires. Processes such as habitat loss, modification and fragmentation and the spread of non-native species will result from the impacts of climate change. India has 14 major forest types classified based on climate and altitude. 72% of forests are tropical moist deciduous, dry deciduous and evergreen forests. The major scenario of climate change in India is deduced from greenhouse gas increase. This scenario forecasts a general increase in temperature and rainfall in all regions. This could result in increased productivity and shift forest type boundaries along altitudinal and rainfall gradients, with species migrating from lower to higher elevations and the drier forest types being transformed into moister types. Thus, climate change could cause irreversible damage to unique forest ecosystems and biodiversity, rendering several species extinct, locally and globally.

Studies of ecological changes and sea level rise should be done to provide continuous inputs for necessary management intervention. Sustainable development of local communities, effective management of natural resources with concerns for conserving biodiversity, and rehabilitation of degraded ecosystems in the context of climate change phenomenon are all closely associated with one another. Forest planning and development programmes have to be based on traditional knowledge and

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ensure people's participation to appropriately adopt various policy and management practices to minimize the adverse impacts and vulnerability to climate change.

Keywords Indian forest • Tropical forest • Climate change • Biodiversity • Butterfly • Birds • Tree line migration • Invasion • Phenology • Greenhouse gas • Temperature

1 Introduction

Global biodiversity is changing at an unprecedented rate as a complex response to several human-induced changes in the global environment (Sala et al. 2000). Biological diversity is generally taken to mean the combination of genetic variation, species richness and taxonomic diversity, and ecosystem diversity (IUCN/UNEP/WWF 1991). Landscape diversity is often added to the definition (Noss and Cooperrider 1994; Markham 1996).

Biodiversity at all levels is currently being lost at an unprecedented rate. Just one measure of this loss is the rate of species extinctions. Background extinction rates through geological time have been roughly estimated at the rate of one mammal and two birds every 400 year (Groombridge 1992; Markham 1996). Documented extinctions for the last 400 year already include 58 mammals and 115 birds (WRI 1994; Markham 1996). This is undoubtedly a major underestimate. Highest levels of biodiversity are in the tropics, particularly the tropical forests, and estimates for the total number of species range between 5 and 30 million, less than two million of which have been described (Wilson 1988; Markham 1996). The top end of this range is based largely on estimates of insect species richness in tropical forests. Current rates of extinction from the tropical forest biome alone have been estimated as between 1% and 11% per decade' (Groombridge 1992; Markham 1996).

In fact, ecologists are becoming increasingly concerned with maintaining diversity at all levels, from phenotype to community patchiness and landscape heterogeneity. In aiming to reduce the impacts of climate change, a greater understanding of the role of biological diversity in ecosystem functioning will be required (Walker 1992; Markham 1996). Human-induced climate change adds another layer to the already complex interplay of forces, natural and anthropogenic, that shape the natural world. Nature has long been regarded as stable, or constant in its make-up. It is, in fact, highly dynamic, with most ecosystems being in some form of transient state, albeit on a range of time scales. The need to prepare for adaptation to climate change is highlighting this issue for the scientific community and the public at large. Current attempts to understand the importance and functioning of biological diversity and the influence of climate change are hampered by ongoing environmental degradation. Principal causes of biodiversity loss worldwide include habitat destruction, pollution, invasive species, and overexploitation of resources such as fisheries and forests. High amongst the driving forces behind these problems are demographic change and population growth, inequitable consumption patterns, inefficient energy use and commodity trade structures. The net result of these many stresses is a loss of biological diversity (Markham 1996). In recent years, biologists have begun to shift their attention from species-based conservation approaches towards strategies that are centered upon the maintenance of the full range of undiminished ecosystem processes and biological diversity (Agardy 1994; Markham 1996).

The ability of ecosystems to respond to and recover from disturbance is termed as resilience, and there is considerable evidence that species diversity strengthens resilience, especially where redundancy or overlap in functional groups of species within ecosystems exists (Tilman and Downing 1994; Markham 1996). Where several species are able to perform the same functions in an ecosystem, they will exhibit different tolerances to disturbance. This redundancy provides a buffer against change (Walker 1995; Markham 1996). Loss of biodiversity, therefore, will most likely reduce ecological resilience and ability to adapt to climate change. The maintenance of biological diversity, redundancy and resilience is vital for the mitigation of global climate change impacts (Markham 1996).

Several ecological changes have been linked to regional climate change. These changes have occurred at all levels of ecological organization: population and life-history changes, shifts in geographic range, changes in species composition of communities and changes in the structure and functioning of ecosystems. There have been changes in the types, intensity and frequency of disturbances that are influenced by regional climatic factors, either anthropogenic or natural, and land-use practices, and these in turn affect the productivity of and species composition within an ecosystem, particularly at high latitudes and high altitudes (IPCC 2001; TERI 2002). Frequency of pest and disease outbreaks has also changed, especially in forested ecosystems. The types of terrestrial ecological impacts and evidence of their occurrence from other parts of the world are given below.

2 Ecological Impacts of Climate Change

2.1 *Species' Range Shifts*

Most species' ranges are regulated by climatic factors. This is particularly true for certain taxa such as insects and amphibians. Studies have shown that there have been range shifts in a number of species. It has been shown that of 35 non-migratory butterflies in Europe, 63% have demonstrated a range shift to the north by 35–240 km in the past century, while only 3% have shifted to the south (Parmesan et al. 1999; TERI 2002).

Parallel studies with breeding birds in Britain have indicated that there has been a northward shift in the margins of species' ranges by an average of 18.9 km over the past 20 years. The investigators attribute this shift to climate change for a number of reasons; recent changes in the timing and success of bird reproduction are associated with warmer springs; the overall spatial distribution of British birds is correlated with temperature; summer temperature is a significant predictor of breeding distribution of 45% bird species; and the observed range shifts have occurred during a period of climate warming (Thomas and Lennon 1999; TERI 2002).

Researchers have found that in 26 sites surveyed in the Swiss Alps, the relationship between species richness and elevation showed a pronounced shift to higher elevations over the past 40–90 years, consistent with the effects of warming. The rate of upward shift was estimated to be 1–4m per decade (McCarty 2001; TERI 2002). Studies have also found dieback in mountain trees that are consistent with the effects of climatic warming (McCarty 2001; TERI 2002).

2.2 Tree Line Migration

Tree line is defined as the elevation (in meters above sea level) of the uppermost individual of any tree species with a minimum height of 2 m. The 2 m criterion implies that individuals are not entirely snow covered and thus they record the free-air climate all year-round at a level above ground that is equivalent to standard meteorological screens (Kullman 2001; TERI 2002). There are two types of changes that have been observed at the tree line: phenotypic change and genotypic change. The former is where trees at their limits grow bigger and taller and the latter is where newly established genetic individuals grow to tree size at ever higher elevations during periods of ameliorating climate.

Researchers have found that in the Southern Scandese mountains of Sweden, tree-limit has risen by more than 100m and forest expansion into alpine tundra, stand out as unexpected and virtually unpredicted anomalies given regional geoecological trends since the Holocene (Kullman 2001; TERI 2002). They surmise that for the twentieth century, tree-limits in this region may be higher and climate warmer than for any other century during the past 4,000 years. At the southern and eastern periphery of the Scandes, many mountains with a previously unforested alpine summit area have become entirely covered with birch/conifer stands. Previous alpine tundra, subalpine meadows and heaths in the area have been converted into a complex mosaic of tundra and more or less dense tree stands with even-aged young stems and a few larger trees from the nineteenth century or earlier (Kullman 2001; TERI 2002).

2.3 Community Composition Change

Broad patterns of terrestrial vegetation types are determined by a combination of temperature and precipitation (IPCC 1996). Examples of climate-driven changes in community composition include the shift from arid grasslands to desert shrub land in the South-western United States. The shift has been attributed to changes in precipitation patterns, and is accompanied by the local extinction of several formerly abundant animal species (McCarty 2001; TERI 2002).

In the short grass steppes of Colorado, United States it has been found that there has been a significant decline in the net primary productivity of the dominant native grass *Bouteloua gracilis*. This decline in productivity is correlated with a rapid increase in temperature in the area. Broadleaved plants in turn have shown a significant increase in productivity and abundance in the area (McCarty 2001; TERI 2002).

2.4 Invasion of Exotics

With climate change, non-native species from adjacent areas may cross frontiers and become new elements of the biota. While human activities result in long distance species' movements, subsequent reproduction and spread in a new location could imply a change in site conditions that lead to a more favorable situation for the invading species, possibly due to climate change (Walther et al. 2002; TERI 2002). Clear evidence of a climate trigger appears in cases where a suite of species with different histories of introduction spread *en masse* during periods of climatic alteration. In some sub-Antarctic islands, for instance, it is estimated that introduced species account for 50% or more of the higher plant diversity and a considerable proportion of the insect and mite fauna. In southern Switzerland it has been observed that there has been a vegetation shift from indigenous deciduous to exotic broad-leaved vegetation. The shrub layer is dominated by the exotics which appear to benefit from the milder winters (Walther et al. 2002; TERI 2002).

2.5 Changes in Phenology

Changes in the phenology of plants and animals are perhaps the most obvious and well studied ecological impacts of climate change. For instance, the spawning and pond arrival time of amphibians in temperate countries have been shown to happen earlier at the rate of about 9–10 days per 1°C increase in temperature (Beebee 1995; TERI 2002). In the southern Scandese, during 1997 and 1998, birches near the tree limit displayed annual shoots with a length of 20–30 cm i.e. about three times greater than the normal value for these sites (Kullman 2001; TERI 2002).

Similar growth progression is demonstrated at some sites close to the birch tree limit where *Salix* spp. in some cases have reached tree-size during the past few years (Kullman 2001; TERI 2002). Analysis of over 30 years of data in Europe has revealed that leaf unfolding has advanced by 6 days and autumnal events such as leaf coloring have been delayed by 4.8 days. This implies that the average annual growing season has lengthened by 10.8 days since the early 1960s (Menzel and Fabian 1999; TERI 2002). Satellite data also indicates an increase in photosynthetic activity of terrestrial vegetation between 1981 and 1991 in northern high latitude areas (450–700N) (Myneni et al. 1997; TERI 2002).

Hence, the major ecological changes liked to climate change include species range shifts, tree line migration, community composition change, invasion of exotics and changes in phenology.

3 Climate Change and Forests

These ecosystem changes also have serious implications for the livelihoods of human communities. In addition to their crucial ecological role, forests make a considerable contribution to the Indian economy. In 1999–00, forestry and logging accounted for nearly 1.10% of GDP at current prices (CSO 2000; TERI 2002). Moreover, non-timber forest products provide about 40% of total official forest revenues and 55% of forest based employment. Nearly 55 million people living in and around forests in India depend upon non-timber forest products as a critical component for their sustenance (TERI 1998; TERI 2002).

Climate change can be expected to have significant impacts on forest ecology (including biodiversity), forest distribution and productivity (Krisehbaum et al. 1996; Ravindranath and Sukumar 1998). The projected impacts of climate change on forests also have implications for forest product flows and trade and forest management (Solomon et al. 1996; Ravindranath and Sukumar 1998). In this context, it is important to make assessments of likely impacts of climate change on forests in different countries and regions to allow respective governments and communities to adapt to these impacts. Such assessments are all the more important in tropical countries in which the local communities depend significantly on forests for their livelihoods and where rates of deforestation are high (Ravindranath and Sukumar 1998).

Forests have significant ecological and economic role for Indian populace. Climate change is expected to have severe implications for forest ecology so it is important to assess the impacts of climate change on forests so as to allow the population and governments to devise suitable mitigation strategies.

4 Indian Forest Types and Area

India has a geographical area of 328 Mha, of which 64 Mha are under forest (>10% tree cover). The altitudinal distribution of geographic and forest area (FSI 1988) shows that 78% of geographic and 66% of forest area is at altitudes less than 600m above sea level (asl). Only 37% and 20% of geographic area is under forests in the altitudinal range of 600–1,800, and 1,800–4,000 m asl, respectively (Ravindranath and Sukumar 1998).

The forests of India are broadly classified in to 14 major types (FSI 1988), based on climate and altitude. Table 2 gives the major Indian forest types. Of these, the tropical forests occupy 51 Mha, or 80% of the forested area. In particular, the tropical moist deciduous and dry deciduous forests are extensive and account for 64% of the total forest area. Tropical, wet evergreen forest is also significant with 8% of the total forest area (Ravindranath and Sukumar 1998).

4.1 Potential Impacts of Climate Change on Vegetation

Climate change is expected to make impacts on boundaries of forest types and areas, primary productivity, species populations and migration, occurrence of pests and disease, and forest regeneration. There are two models which have been used to assess the impacts of climate change on vegetation on a global scale: (i) The BIOME model (Prentice et al. 1992; Ravindranath and Sukumar 1998) is an equilibrium model which defines a set of plant functional types characterized by minimal sets of climate thresholds.

Solomon et al. (1993) and Ravindranath and Sukumar (1998), using BIOME and different future climate scenarios under doubling of CO_2 projects the area under tropical forests to expand in the range of 11–16% depending on the climate model used, (ii) the IMAGE model (IMAGE 2.0, Alcamo 1994; Ravindranath and Sukumar 1998) goes further by incorporating the BIOME vegetation classification into a model of interacting human population, land –use, vegetation, and climate. Its application is most useful where land use changes are important. Using IMAGE, Zuidema et al. (1994) projected the area under tropical forests to decline by 24% by 2020 and 48% by 2050, compared to the 1990 area (Ravindranath and Sukumar 1998).

When annual forest productivity is considered, according to one study (Melillo et al. 1995; Ravindranath and Sukumar 1998) the annual growth is likely to increase in all zones due to fertilization effect from increasing atmospheric CO_2 and increase in water use efficiency. Conversely, forests may also suffer growth losses from effects of increasing climate stress on growth, from increased stress induced mortality and other factors (Solomon and Leemans 1990; Ravindranath and Sukumar 1998).

Paleo-vegetation and climate data are one means of understanding how natural vegetation is likely to respond to future climate change. Pollen analytical studies in the Western Ghats (Vasanthy 1988; Caratini et al. 1991; Ravindranath and Sukumar 1998) and stable arbon isotope analysis of peats dated upto about 20,000 year BP (Sukumar et al. 1993, 1995; Ravindranath and Sukumar 1998) are the main sources of information. However, rigorous data needed to analyze climate change impacts on the tropical forest regions of the sub-continent are as yet not available (Ravindranath and Sukumar 1998).

5 Projected Changes in Climate over India and Impact on Forests

Any assessment of the potential impacts of climate change on forests requires a climate change model and a vegetation change model. While the former projections can be obtained from the several General Circulation Models in use currently, the latter – which links climate with vegetation such as BIOME and IMAGE – have limitations when applied to India. Due to inadequate climatic data sets for the Western Ghats in southern India, BIOME fails to adequately discriminate between the diverse natural vegetation types here. IMAGE makes unrealistic projections of forest cover change in the country. This restricts us to make qualitative statements about climate change impacts on forest types in India (Ravindranath and Sukumar 1998).

Assessments of regional changes in climate parameters are more important than the global mean changes; further seasonal changes are of consequence as compared to the mean annual changes. The commonly considered scenario of climate change in India is based on green house gas increase. It is therefore important to speculate on the possible impact on forests in the country based on this scenario (Ravindranath and Sukumar 1998).

6 Climate Change Under Greenhouse Gas Forcing

The climate parameters used in this scenario are largely based on projections made by Hulme and Viner (1995) for the 2060s. The method used by them has three components: (a) an observed climatology based on Legates and Willmott (1990) at an original resolution of 0.5 latitude/longitude which has been reduced to 2.5 latitude by 3.75 longitude (b) a simple upwelling-diffusion energy balance model for the Assessment of Greenhouse Gas Induced Climate Change (or MAGICC, Wigley 1994) and (c) a coupled ocean-atmosphere General Circulation Model of the Hadley Centre (U.K. Meteorological Office (Murphy 1995; Murphy and Mitchell 1995). The scenario construction is flexible enough to handle uncertainty both in future greenhouse gas emissions and also in the value of climate sensitivity. The projections of Hulme and Viner (1995) are given in Table 1. The parameters considered are changes in temperature, rainfall, length of dry season, soil moisture and interannual variation in rainfall. The projections considered are for southern, central, northwestern and northeastern zones of India (Ravindranath and Sukumar 1998).

6.1 Temperature

The southern peninsular India is projected to experience relatively moderate increases of 2.0–2.5°C in winter (DJF; December, January, February), 3.0–3.5°C during early summer (MAM; March, April, May) and 0.5–1.0°C during the summer monsoon (JJA; June, July, August) season. Central and northern India may experience warming in the region of 3.0–3.5°C during all seasons (Ravindranath and Sukumar 1998).

Table 1 Projected changes in climate parameters for the 2060s derived from maps prepared by Hulme and Viner (1995) for different regions of India (Ravindranath and Sukumar 1998)

1. Changes in temperature (over 1990 levels)				
	South	North	Central	Northeast
December–February (winter)	2.0–2.5°C	3.0–3.5°C	3.0–3.5 °C	2.5–3.0°C
March–May (summer)	3.0–3.5°C	3.0–3.5°C	3.0–3.5°C	2.5–3.0°C
July–November (monsoon)	0.5–1.0 °C	3.0–3.5°C	3.0–3.5°C	2.0–2.5°C
2. Changes in rainfall (compared to 1990 level)				
	South	North	Central	Northeast
June-August (Southwest monsoon)	10–30%	10–30%	50–70%	10–30%
September–November (Northeast monsoon)	50–70%	10–30%	50–70%	–30% to 10%
3. Changes in soil moisture (compared to 1990 level)				
	South	Central	Northeast	
December–February			–5% to 25%	
March–May	15–25%		–5% to 25%	
June–August	15–25%	15–25%	15–25%	

6.2 Rainfall

The Indian subcontinent is dominated by southwest (June to September) and northeast October to December) monsoonal rains. According to projections for the Southwest monsoon season, rainfall will generally increase in the southern (10–30%), central (50–70%) and northeast (10–30%) regions. During the Northeast monsoon season, rainfall is projected to increase by 50–70% in southern India, where this is of significance. Projected increases in other parts of the country are probably not of much consequence during this period. Thus, the rainfall is generally expected to increase in the Southwest as well as Northeast monsoons though at varying intensities (Ravindranath and Sukumar 1998).

6.3 Length of Dry Season

The dry season length (defined as number of months with less than either 50 or 100 mm rainfall) is generally expected to decline over central India, but increase in parts of southern India. In other regions there is no significant change.

6.4 Soil Moisture

Soil moisture is crucial for a range of ecological processes such as seed germination, natural regeneration, growth rates of plants and decomposition rates. Soil moisture is projected to increase marginally by 15–25% over parts of southern and central India. This increase is confined to the monsoon months of June through November. During the rest of the year there is either no change in soil moisture or a marginal decline, even though rainfall is expected to increase by 30–50%. This could possibly be due to the increase in temperature leading to enhanced evapotranspiration (Ravindranath and Sukumar 1998).

6.5 Interannual Variablility

Changes in interannual variability of rainfall are important for a wide range of biological and hydrological processes. The interannual variability for the Indian subcontinent is projected to decline is some regions and experiences no change in others (Ravindranath and Sukumar 1998).

Hence under green house gas forcing scenario a general increase in temperature and rainfall in all regions is indicated. This could potentially result in increased productivity and shift forest type boundaries along altitudinal and rainfall gradients, with species migrating from lower to higher elevations and the drier forest types being transformed to moister types.

7 Potential Impacts of Climate Change on Forests Under Hulme and Viner (1995) Scenario

7.1 Southern Indian forests

The forests in southern India are mainly in two distinctive belts, one along the Western Ghats and the other along the Eastern Ghats. The former tract is biologically more diverse and has been much more extensively studied than the latter. The Western Ghats rise to over 2,000 m asl and their complex topography contributes to a wide spectrum of tropical vegetation types, from wet evergreen forest along the western slopes receiving high rainfall (typically greater than 2,000 mm/annum) and montane stunted evergreen forest and grassland (at altitudes higher than 1,800 m above mean sea level) through semievergreen, moist deciduous, deciduous and dry thorn forest in areas of lower rainfall to the east of the ghats (Ravindranath and Sukumar 1998). Increased temperatures of 2.0–3.5°C during winter and summer would potentially stress vegetation through increased evapo-transpiration. The increased rainfall, however, coupled with elevated $CO_{2,}$ increasing water use efficiency, could compensate for this loss. In the balance, the marginal increase in soil moisture projected for this region could result in increased productivity in all forest types. Further a shift in vegetation type boundaries could be expected along a west-east gradient with moist forest types expanding farther east and along an altitudinal gradient, with species adapted to the warmer, lower elevations migrating to higher altitudes. An increase in dry season length could also place forest types such as dry and moist deciduous forests at increased risk of dry season fires (Ravindranath and Sukumar 1998).

The montane regions of the Western Ghats featuring a mixture of stunted evergreen forest and grasslands with sharp ecotones are a sensitive indicator of the past climate change (Sukumar et al. 1993, 1995).

The montane regions (higher than 2,000 m asl) of the Western Ghats in southern India feature stunted evergreen forests interspersed with grasslands. The forests are largely confined to the sheltered folds of the mountains and stream courses, while the grasslands cover the hill slopes (Sukumar et al. 1995). The forests comprise of C3 plant types which include most dicotyledonous plants and temperate grasses while the grasslands have C3 or C4 plant types that comprise mainly of the tropical grasses.

The vegetational history of this ecosystem in relation to climate change during the late Quaternary through stable-carbon isotope analysis of peat deposits as indicators of C3 or C4 plant types was studied. It was found that the grasslands of C4 type were predominant during the last glacial maximum [20–18, thousand years before present (Kyr BP)] and again during 6–3.5 Kyr BP as a result of lower rainfall and possibly CO_2 levels. These periods were characterized by low atmospheric CO_2 levels (Robinson 1994; Sukumar et al. 1995), lower mean temperatures and low rainfall over the Indian subcontinent. While forests and possibly C3 grasslands expanded during the deglaciation, attaining their peak distribution at 10 Kyr BP. This period was characterized by higher global CO_2 levels (Robinson 1994;

Sukumar et al. 1995), higher temperature and higher precipitation from the Indian summer monsoon.

The shift in C3 and C4 plant types seems related to change in moisture and atmospheric CO_2 with lower moisture and CO_2 levels favoring the latter plant types. The oscillating climate and vegetation has influenced the structure and composition of the montane ecosystem. It is therefore important to study the implications of climate change on the tropical montane ecosystem. Over the next few decades, mean temperatures in the tropics are expected to increase by at least 1–2°C as a result of increase in atmospheric CO_2, methane and other green-house gases (IPCC 1992; Sukumar et al. 1995). General Circulation models predict an intensification of the Indian summer monsoon as a consequence of the increased temperature (Hulme and Viner 1995) which is consistent with the palaeoclimate record. These climatic changes can be expected to favor the expansion of C3 vegetation over C4 vegetation for several reasons. Higher CO_2 levels would enhance photosynthesis rates in C3 plants to a greater extent than in C4 plants. Higher temperatures would lower the incidence of frost and promote the survival of C3 forest plants. Higher precipitation and soil moisture would favor the growth of C3 plants. Thus, the montane evergreen forest can be expected to expand into the grasslands while C3 grasses and herbs could potentially replace C4 grasses in the grasslands (Heaney 1991; Sukumar et al. 1995).

The human impact on the natural vegetation such as conversion of grasslands to monoculture plantations of wattle and eucalyptus may, however, interfere with natural succession caused by global climate change. Endemic mammals such as the Nilgiri tahr would face increased risk of extinction due to reduction in area under natural grassland (Sukumar et al. 1995).

7.2 Coastal areas

Mangrove forests are an important constituent of coastal wetlands. On account of their unique location between sea and land, they are greatly influenced by tidal and fresh water regimes, and hence are fragile in nature (Jagtap et al. 2004).

Logging operation, aquaculture, reclamation of swamps, paddy cultivation on the east coast of India and salt production on the west coast are the main reasons for degradation, resulting into shrinking of tidal forests throughout the Indian coast (Singh 2000; Singh 2003). Among various types of coastal wetlands, tidal mudflats (23,620 km^2) and mangroves (4,871 km^2) have major share. India harbors some of the best mangroves in the world which are located in the alluvial deltas of rivers such as the Ganga, the Mahanadi, the Godavari, the Krishna and the Cauvery as well as on the Andaman and Nicobar groups of Islands (Singh 2000; Singh 2003). Over a dozen Marine Protected Areas in India cover over half of the total mangroves of the country. Out of eight states and union territories which support mangroves, West Bengal (2,115 km^2), Gujarat (1,031 km^2), Andaman and Nicobar Islands (966 km^2), Andhra Pradesh (397 km^2), Orissa (215 km^2) have maximum areas of mangroves (FSI 1999; Singh 2003).

The climate, salinity, tidal fluctuation, substrate or soil, and wind velocity are major factors which determine extent and type of tidal forest. Climatic factors like temperature fluctuation, humidity, precipitation, number of rainy days, regular wind flow, radiation and fresh water flow in the region act as the most significant factors for development and succession of mangroves (Singh 2003).

The concentration of green house gases and aerosols has increased by nearly 31% during last millennium which may further increase in the current century at faster rate. Global temperature rise is expected between 1.4°C and 5.8°C by 2100 which is higher than increase during last century. Similarly continental precipitation increased by 5–10% over the twentieth century in the Northern Hemisphere, although decrease is also recorded in some regions (IPCC 2001). Global mean sea level has also increased and projected a much higher rate in twentieth century (Singh 2003).

Impact on highly diverse and productive ecosystems such as mangrove forests will depend upon the rate of sea level rise relative to growth rates and sediments supply, space for and obstacle to horizontal migration, changes in climate-ocean environment. Sea level rise will affect mangroves by eliminating or modifying their present habitats and creating new tidally inundated areas to which some mangrove species may shift (IPCC 2001; Singh 2003).

A study by Ellison and Stoddart 1991 predicted that in case of scenario of relative sea level rise of 9–12 cm/100 years the mangroves not receiving significant levels of sediment input will be stressed, and at rates of sea level rise greater than 12 cm/century will begin to retreat.

Most predictions suggest that future rises in relative sea level will be of the order of 100–200 cm/100 years. If this projection becomes reality, mangroves of the world may suffer serious loss and majority of the species may fail to adapt new environment. The extensive mangrove systems of the Sundarbans in the Bay of Bengal are examples of river dominated systems where relative sea level may rise less owing to the influx of large amount of silt.

Scenario of overall impact would be different on islands where mangroves are already restricted in area by coastal topography and tidal amplitude. Mangroves in these areas, especially in Andaman and Nicobar Islands may come under stress or may not persist in moderate to high rate of sea level rise. As about 260 km of the coast of Andaman and Nicobar Islands are lined with mangroves and they have restricted scope of adjustment in response to sea level rise, the impact of climate change on extent and species composition of mangroves may be devastative when sea level rise exceed about 10 cm/100 years (Singh 2003).

Considering sea level rise, the mangroves from Kasargod Taluka (Kerala, India), were evaluated for their structure, composition and likely impacts of predicted climate variation. The mangrove cover in Kerala, though sparse, is relatively better represented in the Kasargad Taluka. Patchy and fringing type of vegetation could be attributed to the microtidal nature, relatively steep topography of the coast. About –0.45 km sup (2) of mangrove area was estimated from the study region. The flora was represented by seven spp and dominated by *Avicennia officinalis*. The stand density varied from 276–583 nos. ha sup (−1) with relatively high (720 nos. ha sup (−1)) towards the upstream regions of kayals and backwaters. Substratum mainly composed of sand (37.7–95.9%) with rich (0.41–2.48%) organic carbon. Benthic faunal density ranged from 130–396 nos 10 cm sup (−2) and was dominated by polychaetes and nematodes. The mangroves exist approx. greater than 1 m above present low water level. Increased sea level may drastically impact mangrove habitats by altering the hydrological features and related processes. The vertical rise in the water column due to sea level rise and the limitations of landward margins may result in water logging, ultimately killing mangroves and associated fauna (Jagtap et al. 2004).

An extensive hypersaline mudflat occurs between mangrove line and main coast in Kachchh in Gujarat, which are on rise due to siltation and tectonic movement. In the background of this fact, sea level rise of 12 cm/100 years or even more may not have any negative impact. Increased land accretion may also contribute to rise on mudflats. Thus, this region may have least impact of sea level rise, but when relative rise is very high, the mangroves may shift towards the Rann of Kachchh, which was part of the sea in the past. Other mangrove areas do not have such an extensive barrier to allow this scale of adjustment against sea level rise (Singh 2003).

Mangroves in tropical region are extremely sensitive to global warming because strong temperature dependence of physiological rates places many tropical species near their optimum temperature. Increased species diversity at the community level will add to the competitive ability of mangrove communities as a whole. Outside the present latitudinal limits for mangroves, comparable saline coastal environments are generally occupied by salt marsh vegetation. It is likely, given the more herbaceous nature of the vegetation in these communities that mangroves will compete such species in the medium to long term and that a gradual replacement of salt marsh vegetation by scrubby mangroves, first of *Avicennia* and later of *Rhizophora* may be expected to occur (Pernetta 1993; Singh 2003).

It is also expected that average global rainfall will increase with marked regional variations (IPCC 2001; Singh 2003). If this happens, climate change is likely to lead to an increase in species migration pole wards. This may result into better environment for mangroves in semi-arid region like Gulf of Kachchh. In absence of accurate prediction on extent and rate of climate change, it is not possible to develop a model for likely scenario of mangroves in India. Many species are sensitive to fast changes, especially to anthropogenic disturbance and sea level rise. If pace of sea level is high, these species may not be successful to compete and may loose in favor of hardy and great colonizer, especially *Avicennia marina, A. alba, Acanthus ilicifolius* and *Suaeda sp.* in semi-arid in Gujarat and *A. officinalis* and other species in the moist region. It is expected that species diversity may suffer in some areas, especially in Andaman and Nicobar Islands (Singh 2003).

Mangrove ecosystems act as multiple use ecosystems (provide sink for carbon; barrier against cycle, storm and salty winds, coastal land stability; sustainable agriculture behind shelter belt and fulfill basic needs of coastal community (Singh 2003).

Orissa has a wealth of mangroves along its coasts. Bhitarkanika, an important mangrove in Orissa harbors 62 out of 80 species of mangroves of the world. It is also a habitat of 215 species of both migratory and resident birds and nesting ground of olive ridley turtles (Khalid et al. 2008). But, mangroves are vulnerable to climate change due to sea level rise together with increasing anthropogenic pressure. Increasing temperature can affect mangroves by changing species composition, changing flowering season, and by increasing productivity (Khalid et al. 2008). Mangroves can act as efficient shields against cyclonic waves; therefore there conservation is a must for any adaptation framework to be developed for coastal Orissa (Khalid et al. 2008).

Strict protection of existing mangroves against encroachment and cutting and its expansion by regenerating potential intertidal areas through plantation of suitable species, including vulnerable and threatened species appears to be necessary management options.

Adaptability capability of the species, which may not adapt quickly to climate change, can be improved through management intervention, especially by facilitating their regeneration in new areas. The scientific studies and consistent monitoring the ecological changes and sea level rise should be done to provide continuous inputs for necessary management intervention. The response of tidal vegetation to climate change will vary from area to area and hence area specific plan based on inputs of continuous monitoring of changes should be prepared for implementation (Singh 2003).

7.3 Central Indian forests

In states such as Madhya Pradesh and Maharashtra are mostly moist deciduous and dry deciduous forests. Increase in rainfall and soil moisture during the Southwest monsoon could potentially transform these to moister vegetation types. Sal (*Shorea robusta)* forest characteristic of the moister belt could replace teak (*Tectona grandis)* forest in the drier belt (Ravindranath and Sukumar 1998).

7.4 Northwest Indian forests

Northwest Indian forests are mostly dry deciduous and dry thorn forests. No change in soil moisture storage is indicated for this region. Thus, there may be no scope for any significant change in forest type or productivity (Ravindranath and Sukumar 1998).

7.5 Northeast India

Northeast India has a wide spectrum of tropical and subtropical forests and grasslands associated with the flood plains of rivers. The climate change scenario for northeast India is not very clear. There seems to be much greater variability in the various climatic parameters over even a small area. This region already experiences very heavy rainfall, and any small changes in rainfall may not be of much consequence for vegetation. The projected increase in temperature, however, in all seasons, is likely to result in shifts of lower altitude tropical and sub-tropical forests to higher altitude temperate forest regions, resulting in contraction or die off of some temperate vegetation types (Ravindranath and Sukumar 1998).

Predicting the effect of climate change on rain forest ecosystem structure and function on a broader scale is equally difficult in the absence of precise studies. The impact of climate change would, to a large extent, be location specific, because of the complex interactions.involved. Global warming is often associated with increase or decrease in rainfall regime and soil moisture conditions (Ramakrishnan 1998).

The predicted temperature changes are generally in the range of 23°C. The scenario constructed by Hulme and Viner (1995) suggests the following changes in the Indian subcontinental region, an increase in rainfall, in some areas up to 50%, a possible reduction in the dry season length by several months, and a consequent increase in soil moisture depending upon the soil characteristics.

High rainfall, thus, could accentuate environmental stress caused through perturbation in the upland areas by rapidly depleting the soil of its nutrient pool through run off and infiltration losses as shown in northeastern India. An extreme example of the above phenomenon is Cherrapunji in the state of Meghalaya in northeastern India (Ramakrishnan 1992; Ramakrishnan 1998). The harsh climate, with much of the annual average rainfall of 1,150 cm (with a very high 2,250 cm in an exceptional year, as in 1974) coming down in about 4–5 months during the monsoon, is further compounded by a highly leached fragile soil. The sacred grove of Mawsmai, protected for reasons of traditional religious beliefs, is a sad reminder of what Cherrapunji looked like in the past. Though the forest is stunted because it is supported by an unbalanced soil derived from limestone, the trees and shrubs form a dense multilayered canopy protecting the soil from the ravages of the extreme climate. Had it not been for the traditions of the Khasis, even this sacred grove – which is believed to be the abode of their Gods and the spirits of their dead ancestors, and therefore acts as a taboo for removal of even dead twigs from the forests – would have disappeared long ago. Unfortunately, many of these groves, which were part of every village in the Khasi Hills, have already disappeared with the arrival of the modern value system. With that, we have almost lost a unique way of preserving this national heritage of rain forest ecosystems (Ramakrishnan 1998).

The Cherrapunji ecosystem, which now stands desertified due to deforestation, is now unable to recover to its original state, as represented by the relict sacred grove. The fact that *jhum* around Cherrapunji is banned by the village council is suggestive of the part played by this land use in creating the present landscape. The sharp boundary between the sacred grove and the balded landscape indicates that the system will not recover through natural processes of revegetation. Artificial restoration could carry enormous initial costs. Linked with this drastic loss in biological diversity is immense human suffering. Water is a scarce commodity during dry months, despite its distinction as one of the wettest spots on earth along with the nearby Mawsengram (Ramakrishnan 1992; Ramakrishnan 1998). All the water flows down the plains because of the absence of vegetation cover. Soil erosion is therefore intense, and water holding capacity of the soil is low. This, in turn, leads to inability of the system to recover with a forest cover. For fuelwood, the tribal villager has to trek long distances of up to 10 km or more. The ruins of abandoned villages remind one of the population migrations of the past, which occurred under adverse ecological circumstances. The tribe, which is traditionally bound to the land and forests, has been forced to seek other avenues for survival (Ramakrishnan 1998).

With reduction in the rainfall, degradation of the rain forest could result in an *Imperata cylindrica* dominated, tall grass arrested successional stage. In the northeast Indian context, these grasslands often have exotic weeds such as *Eupatorium* spp. And *Mikania micrantha*, along with other native grasses such as *Thysanolaena maxima* and *Saccharum* spp. These grasslands are highly susceptible to fire. Indeed, species such as *Imperata cylindrica* and *Mikania micrantha* are fire adapted to such an extent that regeneration of these two are closely linked with frequent fire events (Ramakrishnan 1992). Sustainable livelihood for these traditional inhabitants, and sustainable development of the region as a whole, is therefore critical for conserving the tropical rain forest ecosystem for its biodiversity and value as a carbon sink (Ramakrishnan 1998) (Tables 1 and 2).

Sustainable development of local communities, effective management of natural resources with concerns for conserving biodiversity, and rehabilitation of degraded/ altered ecosystems in the context of climate change phenomenon are all closely interlinked with one another. Ecological issues are tied up with social, economic, anthropological, and cultural dimensions, since the guiding principles of sustainable development cut across these very disciplinary realms, with obvious tradeoffs.

Table 2 Major Indian forest types (Ravindranath and Sukumar 1998)

1.	Subalpine and alpine
2.	Himalayan moist temperate
3.	Montane wet temperate
4.	Sub tropical, broad leveled hill
5.	Subtropical dry evergreen
6.	Sub tropical pine
7.	Tropical dry evergreen
8.	Littoral and swamp
9.	Tropical thorn
10.	Tropical semi evergreen
11.	Tropical wet evergreen
12.	Tropical dry deciduous
13.	Tropical moist deciduous

While forest based economic activities and cash crop plantation programs may be the most appropriate long-term alternatives to shifting agriculture in northeast India, there is no option except to have a redeveloped agro-ecosystem package for the region which employs traditional knowledge and technology as the starting point for a short term strategy (Ramakrishnan 1992, 1998).

The long term strategy has to be reconciled with short term requirements. Further, institutional arrangements have to ensure peoples' participation through a bottom up approach for their organization, ensuring that each household takes part in the decision making process at the lowest level in the hierarchy, and with special dispensation for the weaker and more vulnerable sections of the society (Ramakrishnan 1998).

7.6 Impact of Climate Change on Phenology of Tropical Forests

Climate change will influence many aspects of the biology of tropical organisms, but the effects on plant phenology could be of particular significance. The great majority of tropical plant species show some degree of periodicity in growth and reproduction, whether or not the periodicity is annual (Longman and Jenik 1987; van Schaik et al. 1993; Corlett and Lafrankie 1998). The timing of periodic events may be essential for cross-pollination and escape from herbivores (Aide 1993; Corlett and Lafrankie 1998) or seed predators (Augspurger 1981; Corlett and Lafrankie 1998). Climate change will happen during the life time of individual long-lived plants and changes in phenology may be the major short-term response. Climate change may result in mistiming of life history events in relation to the new climatic seasonality or the loss of synchronization. The periodicity of plant growth and reproduction, in turn, has a profound impact on those animal species – the majority – that depend on periodically available plant resources: young leaves, pollen, nectar, fruits, and seeds. Unfortunately for our ability to predict the impact of global warming on tropical forests, phenological patterns in the tropics are both far more diverse than in extra tropical ecosystems and far less understood (Corlett and Lafrankie 1998).

The climate change scenario predicts a warming of 1.5–2.5°C. The response of rainfall patterns to global warming in the scenario varies over the region, but there is generally an increase in dry season length in seasonal Southeast Asia (Corlett and Lafrankie 1998). This increase is well within the range of current interannual variability, although the new extremes will presumably be outside this range. If plant responses to the end of the dry season are, as seems probable, largely opportunistic, significant mistiming of phenological events as a result of a moderate increase in dry season length is unlikely. In the more open forest types, however, plants must also be phonologically adapted to the current fire regime (Rundel and Boonpragob 1995; Corlett and Lafrankie 1998) and may be sensitive to the impact of climate change on fire timing, frequency, and intensity. The increase in dry season length in southern India will also threaten evergreen forests that are not phenologically or otherwise adapted to fire.

The large decrease in dry season length predicted for much of the Indian monsoon region is more likely to have a major direct impact on plant phenology. A dry period of inadequate length or intensity may fail to trigger flowering (Foster 1983; Corlett and Lafrankie 1998) or to synchronize it, and may also fail to reduce herbivore populations during the main period of leaf expansion. The impact of a shortened dry season would be greatest where the dry season is already weak, but the scenario suggests that, within tropical Asia, weak dry seasons will generally be strengthened or unchanged and only the strongest dry seasons significantly weakened (Corlett and Lafrankie 1998).

7.7 North Indian Forests

A regional study in Himachal Pradesh in northern India based on the output of BIOME model assessing the impacts of climate change on the temperature and sub-tropical forest vegetation has shown that there would be significant changes in the cover and location of different forest types. The extent to which the biomes shift, shrink or expand would also depend on their sensitivity to climate change. The study concluded that if the present trends (arising out of anthropogenic pressures) continue, the negative repercussions of climate change are likely to be severe (Deshingkar et al. 1997; Ravindranath and Sukumar 1998).

The Himalayan states account for one third of the total forest cover in the country with a predominantly agro-pastoral population. The Himalayan ranges represent a unique amalgamation of geology, geomorphology, soils and drainage systems. The environmental importance of these areas lies not only in their rich bio-diversity value at the global level but also in their fundamental role in the long range ecological security and perpetuity of the entire Indian subcontinent's glaciers and river systems. The degradation and deforestation in Himalayas would destroy the abode of rich bio-diversity and also trigger negative consequences on the productivity of the alluvial plains of India and the productivity of deltaic regions in the east where the river waters merge with international waters in the Bay of Bengal (TERI 2002).

The Uttarkashi Forest Division in Uttaranchal state was studied for potential impact of climate change on forestry. The most striking evidence that was observed during the field study was the change in phenolgy of various species especially so for the flowering of *Rhododendron* sp. It was observed that in both Mukhem and Dharasu ranges.

Rhododendron has been flowering about 15 days earlier and that the flowers appear to be smaller than they were 15–20 years ago. This was attributed to the change in rainfall patterns. Another phenological change noted in these areas was the earlier leafing and fruiting of oak trees. The reason given for this was the reduction in snowfall and increase in temperature. The changes in the area of the birch (*Bhoj*) forest that have been observed around Bhojwasa are mainly due to biotic pressure from ashram residents and the heavy traffic of pilgrims and tourists to the area. Many trees have been cut down for fuel and for using the bark as paper. Natural disaster has also taken its toll on the birch forests near Bhojwasa. In Dharaali, it was observed that the lower limit of *Bhoj* (*Betul utilis*) trees had shifted further uphill.

In the Gomukh area residents noted that they had observed a significant increase in herbaceous species growing around that area. Kail (*Pinus wallichiana*) trees at mid to upper slope between Harsil and Gangotri have been drying. This phenomenon reportedly began about 2–3 years ago and was observed by the study team at the Saat Tal area above Dharaali village Dharali Block, compartment 4. It is surmised that this drying is being caused by a disease, a fungal one which affects only *Kail* and younger trees are affected more than older ones. One of the reasons for the occurrence of disease in these areas could be the favourable climatic conditions i.e., increase in moisture or humidity or milder winter in the region.

One of the observations made at lower elevations was that in the area around Saur village, Jalkurgad Block (compartment- 29), Chir *(Pinus roxburghii*) had begun to grow in areas formerly occupied by oak. About 50 years ago, the stand used to be about 90% oak and mixed species and only 10% pine cover, according to local elders. Now they say the proportion of pine had increased to 50% by replacing the other species. The pine at this site appeared to be about 30 years of age. The respondents attributed this change mainly to a gradual increase in temperature and the consequent drying out of the soil. The study team also made the observation of similar Chir invasion into formerly oak forest in Bhukki block, compartment 1 and 2, near Bhatwari village The participants in the survey in Bhatwari noted that there has been a significant decline (about 40%) in the area covered by oak. Respondents said that this was due to the pressure on oak for fodder and fuel and also due to increased incidence of forest fires (man-made) and grazing which inhibit regeneration of oak. Thus, in the region biotic pressure has allowed the establishment of Chir in an oak forest by fragmenting it and opening up the canopy. It is very likely that favorable climatic conditions of reduced snowfall and general warming in the area has further led to drying of the soil which has enabled Chir to spread even faster into oak stands.

In Bhareti Khand, Dharasu range, Forest Department staff noted a shift from Chir forest to a more xerophytic assemblage, consisting of species like *Ficus* and *Mallotus philippensis* on the east facing slope. The Forester for this area surmised that there may at one time have been an oak forest in this area due to the presence of oak stumps and a natural spring (which are usually found in oak areas). This site could provide evidence of progressive community type shifts over a century as the climate gets warmer and drier.

Participants at the sites in Dharasu and Mukhem ranges noted an increase in the population of exotic species that have invaded the area. The Forest Dept. staff at Bhareti Khand in Dharasu noted the spread of *Parthenium* spp., *Lantana camara* and *kalabans* in recent years. In the Chaurangi-Saur-Dhauntri area in Mukhem range, participants noted the rapid spread of *kalabans* in disturbed areas. The study team observed that the species has formed a dense carpet at the herb layer along forest edges and in open field areas.

This species was not observed at the higher altitude sites earlier to this. Most respondents reported a great decrease in density of tree cover and increasing fragmentation of forests, accompanied by local species extinction. They attributed most of these changes to increased biotic pressure.

It was concluded that vegetative change due to climatic factors has begun to occur in the area and long term monitoring through monitoring plots should also be established in other sensitive ecotypes in the study area such as alpine meadows, so that the pace and direction of climate-driven vegetation change can be detected and characterized (TERI 2002).

8 Recent Assessments of Climate Change Impact on Indian Forests

Global assessments have shown that future climate change is likely to significantly impact forest ecosystems. The present study makes an assessment of the impact of projected climate change on forest ecosystems in India. This assessment is based on climate projections of Regional Climate Model of the Hadley Centre (HadRM3) using the A2 (740 ppm CO_2) and B2 (575 ppm CO_2) scenarios of Special Report on Emission Scenarios and the BIOME4 vegetation response model. The main conclusion is that under the climate projection for the year 2085, 77% and 68% of the forested grids in India are likely to experience shift in forest types under A2 and B2 scenario, respectively. This includes loss of area under a given forest type and replacement by another type from the prevailing forest type. In other words, over half of the vegetation is likely to find itself less optimally adapted to its existing location, making it vulnerable to adverse climatic conditions and to biotic stresses. Indications are a shift towards wetter forest types in the north-eastern region and drier forest types in the north-western region in the absence of human influence. Further, the actual negative impact may be more than what is initially expected from the above description. This is because different species respond differently to the changes in climate. Thus, one expects that a few species may show a steep decline in populations and perhaps even local extinctions. This, in turn, will affect the other taxa dependent on the different species (i.e. a ‘domino’ effect) because of the interdependent nature of the many plant–animal–microbe communities that are known to exist in forest ecosystems. This could eventually lead to major changes in the biodiversity. The positive impact of projected climate change, under the A2 and B2 scenario, is the projected increase in NPP. Thus, the projected climate impacts are likely to have significant implications for forest management in India (Ravindranath et al. 2006).

9 Conclusion

Climate change represents a significant threat to global biodiversity and ecosystem integrity. It can be expected to have significant impacts on forest ecology (including biodiversity), forest distribution and productivity. Since the projected impacts of climate change on forests also have implications for forest product flows and trade and forest management. So, it is in this context, it is important to make assessments of likely impacts of climate change on forests in different countries and regions to allow respective governments and communities to adapt to these impacts. Several ecological changes have been linked to regional climate change. These changes have occurred at all levels of ecological organization: population and life-history changes, shifts in geographic range, changes in species composition of communities and changes in the structure and functioning of ecosystems. India has 14 major forest types classified based on climate and altitude. Of these 72% are tropical moist deciduous, dry deciduous and evergreen forests. The BIOME and IMAGE models have been used to assess the impacts of climate change on vegetation on a global scale. However, both these General Circulation Models have limitations when applied to India. Assessments of regional changes in climate parameters are more important than the global mean changes. The commonly considered scenario of climate change in India is based on green house gas increase. It is therefore important to speculate on the possible impact on forests in the country based on this scenario. Under this model a general increase in temperature and rainfall in all regions is indicated. This could potentially result in increased productivity and shift forest type boundaries along altitudinal and rainfall gradients, with species migrating from lower to higher elevations and the drier forest types being transformed to moister types. Considering the potential impacts of Climate change on forests under Hulme and Viner (1995) scenario for the evergreen forests in south India increased temperatures of 2.0–3.5 °C during winter and summer would potentially stress vegetation through increased evapo-transpiration. The increased rainfall, along with elevated $CO_{2,}$ increasing water use efficiency, could compensate for this loss. In the balance, the marginal increase in soil moisture projected for this region could result in increased productivity. Further a shift in vegetation type boundaries could be expected along a west-east gradient with moist forest types expanding farther east and along an altitudinal gradient, with species adapted to the warmer, lower elevations migrating to higher altitudes. An increase in dry season length could also place forest types such as dry and moist deciduous forests at increased risk of dry season fires. The montane evergreen forest can be expected to expand into the grasslands while C3 grasses and herbs could potentially replace C4 grasses in the grasslands (Heaney 1991; Sukumar et al. 1995).

The human impact on the natural vegetation such as conversion of grasslands to monoculture plantations of wattle and eucalyptus may, however, interfere with natural succession caused by global climate change. Endemic mammals such as the Nilgiri tahr would face increased risk of extinction due to reduction in area under natural grassland.

Impact on highly diverse and productive ecosystems such as mangrove forests will depend upon the rate of sea level rise relative to growth rates and sediments supply, space for and obstacle to horizontal migration, changes in climate-ocean environment. Sea level rise will affect mangroves by eliminating or modifying their present habitats and creating new tidally inundated areas to which some mangrove species may shift.

Central Indian forests are mostly moist deciduous and dry deciduous forests. Increase in rainfall and soil moisture during the Southwest monsoon could potentially transform these to moister vegetation types. Sal (*Shorea robusta)* forest characteristic of the moister belt could replace teak (*Tectona grandis)* forest in the drier belt.

Northwest Indian forests are mostly dry deciduous and dry thorn forests. No change in soil moisture storage is indicated for this region. Thus, there may be no scope for any significant change in forest type or productivity. In case of Northeast India the projected increase in temperature, however, in all seasons, is likely to result in shifts of lower altitude tropical and sub-tropical forests to higher altitude temperate forest regions, resulting in contraction or die off of some temperate vegetation types

Studies in the North Indian forests suggested that reduced snowfall, general warming in the area and change in rainfall patterns have resulted a change in phenolgy of various species especially so for the flowering of *Rhododendron* sp, drying of the soil which has enabled Chir to spread even faster into oak stands, occurrence of fungal diseases leading to drying of Kail trees and progressive community type shifts over a century as the climate became warmer and drier (shift from Chir forest to a more xerophytic assemblage, consisting of species like *Ficus* and *Mallotus philippensis)*. Also an increase in the population of exotic species (*Parthenium* spp., *Lantana camara* and *kalabans)* has been observed in the area.

Global assessments have shown that future climate change is likely to significantly impact forest ecosystems in India based on climate projections of Regional Climate Model of the Hadley Centre (HadRM3) using the A2 (740 ppm CO_2) and B2 (575 ppm CO_2) scenarios of Special Report on Emission Scenarios and the BIOME4 vegetation response model. It has been concluded that under the climate projection for the year 2085, 77% and 68% of the forested grids in India are likely to experience shift in forest types under A2 and B2 scenario, respectively. This includes loss of area under a given forest type and replacement by another type from the prevailing forest type due to adverse climatic conditions and biotic stresses. Indications are a shift towards wetter forest types in the north-eastern region and drier forest types in the north-western region in the absence of human influence.

Thus, climate change could cause irreversible damage to unique forest ecosystems and biodiversity, rendering several species extinct, locally and globally.

Long term monitoring through monitoring plots should also be established in sensitive ecotypes, so that the pace and direction of climate-driven vegetation change can be detected and characterized. Sustainable development of local communities, effective management of natural resources with concerns for conserving biodiversity, and rehabilitation of degraded/ altered ecosystems in the context of climate change phenomenon are all closely interlinked with one another. Forest planning and development programmes have to be based on traditional knowledge and ensure people's participation to address the likely impacts of climate change and appropriately adopt various policy and management practices to minimize the adverse impacts and vulnerability to climate change.

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