Alluvial Gully Prevention and Rehabilitation Options for Reducing Sediment Loads in the Normanby Catchment and Northern Australia

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Final Report

Prepared for the Australian Government's
Caring for our Country Reef Rescue Initiative

December 2013

FINAL VERSION

31 December 2013

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CARING FOR OUR COUNTRY
Reef Rescue Research & Development
Australian Government
Department of the Environment, Water, Heritage and the Arts
Griffith UNIVERSITY
CAPE YORK SUSTAINABLE FUTURES
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ISBN: 978-1-922216-12-0

Published by Australian Rivers Institute, Griffith University on behalf of the
Australian Government's Caring for our Country Reef Rescue Initiative.

<u>Citation:</u>

Shellberg, J.G., Brooks, A.P., 2013. *Alluvial Gully Prevention and Rehabilitation Options for Reducing Sediment Loads in the Normanby Catchment and Northern Australia*. Griffith University, Australian Rivers Institute, Final Report for the Australian Government's Caring for our Country - Reef Rescue Initiative, December 2013, 314pp. http://www.capeyorkwaterquality.info/references/cywq-223

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Executive Summary

Report Overview

This two-year project funded by the Australian Government's Caring for our Country Reef Rescue Initiative was undertaken by Griffith University to assess the options for preventing and rehabilitating alluvial gullies in the Normanby Catchment, with implications for alluvial gully management across northern Australia. Alluvial gullies eroding into terraces and elevated floodplains along river frontage with dispersive or sodic soils are a major sediment source in the Normanby catchment and northern Australia (Plate 1). Traditional Owners, cattle graziers and other local residents in the catchment and along Princess Charlotte Bay are concerned about economic, cultural and environmental impacts of local gully erosion and downstream sedimentation. Large alluvial gullies – and gullies in general – are often considered to be in the 'too hard basket' for basic land management action. However, large reductions in elevated sediment loads at the catchment scale will not be achieved unless gully erosion is addressed cumulatively through innovative proactive land management actions.

Plate 1 Examples of alluvial gullies in the Normanby catchment.

The aims of this report were to: 1) review the current scientific knowledge on alluvial gully erosion in northern Australia, 2) review scientific and grey literature on gully prevention, rehabilitation, and best management practice options applicable to alluvial gullies, 3) implement several field trials for preventing and rehabilitating alluvial gullies, and 4) provide information toward the future development of a comprehensive regional Best Management Practice (BMP) manual to address alluvial gully erosion based on scientific principles and proven field success. Social, economic, and political obstacles to cumulatively reducing gully erosion and sediment yield at the catchment scale are also reviewed.

While this report does not provide detailed BMP solutions for all gully erosion issues in the Normanby catchment or elsewhere, it does highlight in detail the nature of the problem and potential research and management actions for the future. Reducing sediment loads to river systems and coastal environments will not occur unless these cumulative and complex physical, chemical, biological processes together with social, economic, and political management issues are understood and addressed.

Background to Alluvial Gully Erosion

Alluvial gully erosion is both a natural and human land use accelerated erosion process. These alluvial gullies or 'breakaways' initiate on steep river and creek banks along river frontages and erode into river terraces and elevated floodplains with highly erodible soils (Plate 2; Plate 3). River incision over geologic time (base level), dispersive or sodic soils (high exchangeable sodium on clay particles), intense monsoon rainfall and flooding are natural factors priming the landscape for gully erosion. Since the margins of terraces and elevated floodplains are only infrequently inundated or backwatered by flood water, erosion from direct rainfall and overland water runoff from subtle terrace/floodplain slopes dominates gully scarp retreat.

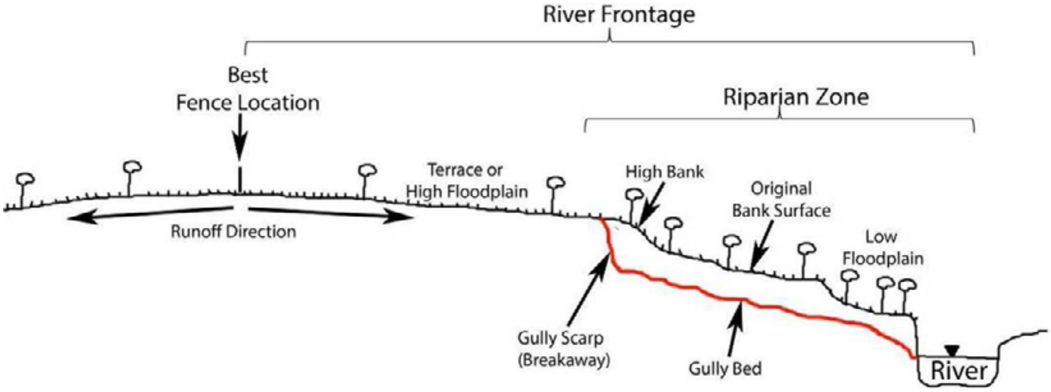

Plate 2 Cross-section drawing of an alluvial gully (bed and scarp) eroding into a terrace from a river bank.

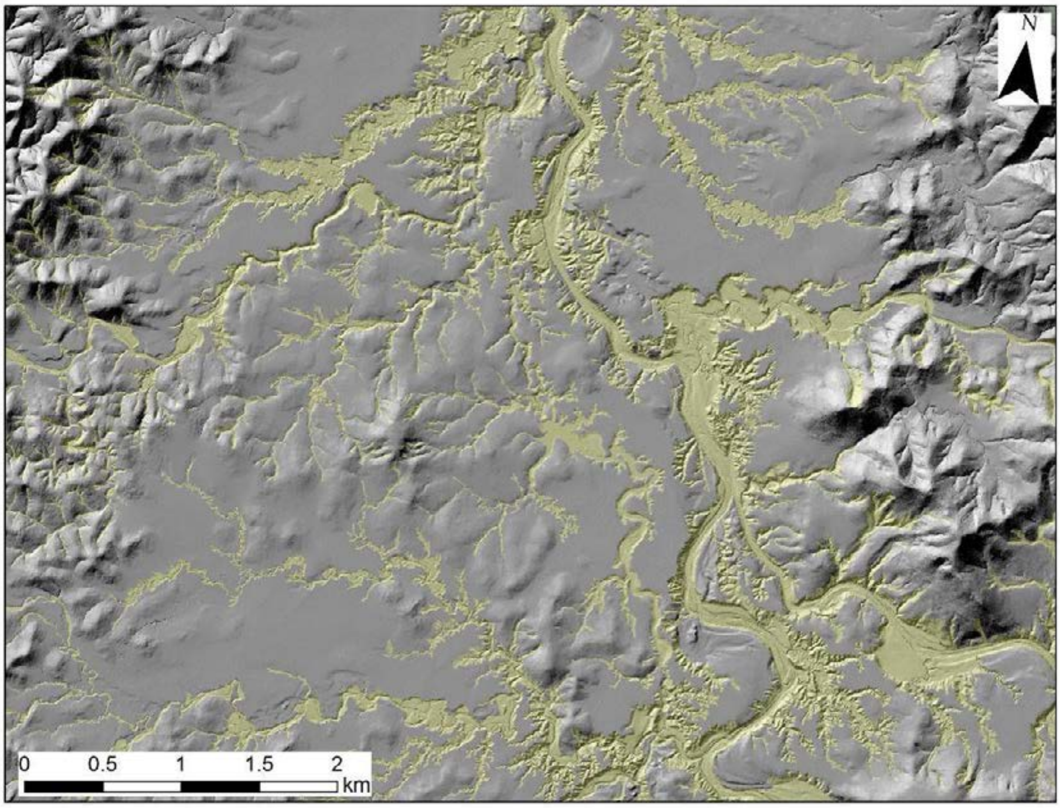

Plate 3 An airborne LiDAR hillshade map of alluvial & colluvial gullies and creek & river channels along the Granite Normanby River valley and frontage country showing the complexity of the channel network.

Sediment dating in alluvial gullies has shown that gully erosion rates have increased greater than 10 times since European settlement in some locations. Historic aerial photographs also document increased gully erosion after land use change. Modern gullies have eroded into older floodplain hollows and drainage channels that were earlier phases of gully erosion, as well as steep river banks. The recent accelerated phase of gullying can be linked to the introduction of cattle that congregate along river frontages, reduction of perennial grass cover, concentration of water along cattle tracks (pads), and an increase in water runoff into gullies (Plate 4), as well as intense late-dry season fires, roads, fence lines, agricultural clearing, and infrastructure development.

Plate 4 Examples of over-grazed riparian frontage with cattle tracks (pads) funnelling water down to gully heads, as well as cattle tracks cut into steep river bank hollows.

Sediment budget research in the Normanby catchment estimated that 37% (1,148,200 t/yr) of fine sediment (<63 µm) entering the river system comes from alluvial and colluvial gullies. Independent sediment tracing data suggests that >87% of fine sediment inputs (<10 µm) originate from sub-surface sediment sources (channel bank erosion, gully erosion, etc.), with hillslope surface sources only a minor contributor. The mapped area of active, bare-earth, alluvial gully erosion viewable by aerial photographs in the Normanby catchment is > 1000 ha. It has been estimated that >10,000 ha of gullies exist in the Normanby once the masking of trees is removed using Light Detection and Ranging (LiDAR) topographic data. These alluvial gullies are mostly concentrated on dispersive or sodic soils along terraces and elevated floodplains of river frontage areas, where cattle grazing is focused.

Principles of Gully Erosion Prevention and Control

There are three main approaches to prevent gully initiation and reduce gully erosion once started, which generally should be used in combination.

1. Reduce water runoff into and through gullies and drainage hollows.
2. Stabilise gully headcuts, sidewalls, and drainage hollows with vegetation and/or physical structure.
3. Reduce the gully channel slope and increase roughness using grade control structures and/or vegetation, which will trap sediment and promote revegetation.

Large-Scale Land Management to Prevent and Reduce Alluvial Gully Erosion

Mapped areas of concentrated alluvial gully erosion and soils with high erosion risk (i.e., dispersive or sodic soils along river frontage terraces, Plate 3; Plate 5; Plate 17) should be targeted for large-scale land management changes and localised intensive rehabilitation actions to cumulatively reduce sediment yields to downstream rivers, wetlands, estuaries, coasts, and off-shore reefs. Land management actions to directly or indirectly prevent or reduce alluvial gully erosion from high risk areas include:

- Increasing perennial grass cover on shallow slopes above gully prone areas such as steep river banks.
- Reducing water runoff toward gully prone areas by improving soil/vegetation hydrologic functions upslope.
- Reducing concentrated water runoff down cattle tracks (pads), roads, and fences.
- Increasing perennial grass cover within gully prone areas (river banks and hollows) to resist erosion and trap sediment.

A paradigm shift and a full suite of altered management actions (cattle, fire, weed, road, fencing) are needed on erosion-prone sodic soils along river frontage, in order to reduce the initiation of new alluvial gullies, slow gully erosion rates where already initiated, and aid in indirect/passive long-term rehabilitation efforts.

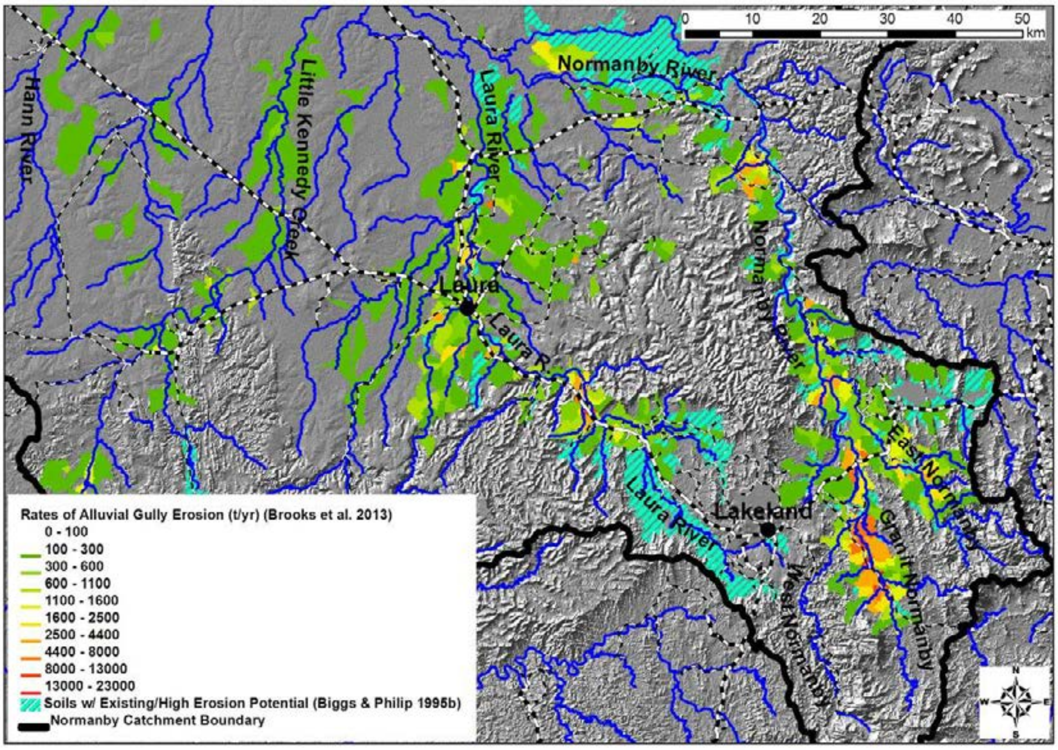

Plate 5 High risk areas of alluvial gully erosion in the upper Laura-Normanby catchment.

Cattle Management along River Frontage with Dispersive or Sodic Soils

Cattle grazing is a primary agent for accelerating gully erosion on highly-erodible sodic soils. Cattle grazing intensity and impacts are often concentrated along river frontage terraces and elevated floodplains. Ideally, permanently maintained cattle exclusion fencing is needed around large concentrated areas of gully erosion to create ‘soil conservation areas’ by fencing according to land type (i.e., sodic soils on river frontage). Several priority river frontage areas have been identified in the Normanby (e.g., the Granite Normanby River, Plate 5; Plate 17). Alternatively, seasonal spelling of cattle could be used if it can be demonstrated to reduce gully erosion. Government or market-based compensation is needed for the economic loss of graziers, such as payment for ecosystem services (carbon, biodiversity, soil retention) or promotion of ‘improved pasture’ management on stable and productive soils.

To document the effectiveness of cattle exclusion for vegetation recovery and soil erosion reduction, cattle exclusion experiments have been initiated around alluvial gullies in the upper Laura-Normanby catchment (Plate 6). Four (4) cattle exclusion areas (3-5 ha) were fenced in 2012 to start a long-term monitoring program (5 to 10+ years). A before-after, control-impact study design was used with vegetation and erosion plots and detailed repeat topographic surveys (LiDAR). Funding is needed for long-term monitoring.

Plate 6 An alluvial gully recently fenced off from cattle grazing, and changes in grass cover on a river terrace above a gully head inside and outside the fence after one wet season. Short-term vegetation improvements within the gully were minor after fencing.

- *Draft BMPs for Cattle Grazing on River Frontage with Dispersive or Sodic Soils*
    - Exclude cattle from mapped sodic soils on river frontage terraces and elevated floodplains.
        - Fence to land type.
        - For best management, fence completely around mapped erodible sodic soils, locating fences on more stable geology.
        - Otherwise, place fences well back from high banks when excluding cattle from immediate river frontage zones, when entire areas of sodic soils cannot be fenced. Include river terraces and flats upslope of gullies (breakaways) inside fence to increase grass cover and reduce water runoff from these catchment areas (Plate 2).
        - Use spear traps and rotated use of fire to move cattle off river frontage.
    - Wet season spelling (Dec-April) of cattle along erodible river frontage, when full cattle exclusion is not feasible.
    - Cattle exclusion or spelling will reduce cattle tracks (pads) over steep banks and across terrace/floodplain flats.

  - Vegetation cover targets >75% at break-of-season (Nov), >1000 kg/ha perennial grass.
  - Install off-stream water points for cattle on stable geology outside of mapped erodible sodic soils and well away from river banks.
  - Reduce cattle numbers during drought. Use Bureau of Meteorology (BOM) climate forecasts and market forecasts to destock early for income benefits, soil protection, and prevention of land and pasture degradation.

Fire Management along River Frontage with Dispersive or Sodic Soils

Fire regimes on dispersive or sodic soils in river frontage terraces and elevated floodplains need to be tailored toward maximizing the health of perennial grass cover (for water runoff regulation and soil stability), minimizing weed dominance or spread, and regulating the amount of grass cover consumed by cattle each year to build up grass cover and fuel loads. In some highly eroded locations, fire should be excluded to maximise any potential vegetation cover. At the landscape scale, a return toward a mosaic (patchy) burn pattern and variable timing of fire regimes is needed, locally tailored to soil type and vegetation community (Plate 7). More scientific experimentation is needed to identify the most appropriate fires regimes for sodic soils on terraces and elevated floodplains in river frontage to promote perennial grass health, reduce water runoff and soil erosion, and minimise gully erosion, while also managing the balance between trees and grass. Some preliminary BMPs are included below.

Plate 7   Low intensity early-dry season burn in a colluvial hollow and perennial grass tussock and incompletely burnt organic mulch cover remaining after the low intensity burn.

- *Draft BMPs for Fire Management along River Frontage with Dispersive or Sodic Soils*
  - Cattle spelling during the wet season (Dec-April) or full cattle exclusion to improve perennial pasture health and build up fuel loads for appropriate fire regimes, if any.
  - In some highly erodible locations, fire could be excluded altogether to maximise any potential vegetation cover.
  - Reduce the occurrence of intense late-dry season fires through river frontage with sodic soil.
  - Create a mosaic (patchy) burn pattern at the landscape scale with variable timing.
  - Mange fire in a controlled fashion in discrete areas.
  - Locally tailor fire regimes to soil type and vegetation community for specific objectives (i.e. increase long-term perennial grass cover, weed control).
  - Use prescribed aerial and/or ground burning in the early-dry season to install fire breaks and take advantage of natural or made-made fire barriers.
  - Move the location of early-dry season fire breaks every year to burn in a mosaic pattern and not burn the same location repeatedly, especially along erodible river frontage.

  - Avoid repeatedly using river frontage and riparian zones as fire breaks. Frequent fires can reduce the long-term health of perennial grass and increase gully erosion potential on terrace and floodplain margins.
  - Do not repeatedly grade fence lines as fire breaks, as this will accelerate erosion.
  - Early-wet season ‘storm-burns’ (1-3 days after first >25mm rain) should be used cautiously in strategic patches along highly-erodible river frontage with dispersive or sodic soils to avoid accelerated water runoff and soil erosion at the start of the wet season. Storm-burns should be used for specific localised purposes (rubber vine control; thickening of *Melaleuca viridiflora*, improving perennial grass germination/health) where long-term improvements of grass cover can be demonstrated to reduce gully erosion.
  - Control cattle grazing of grass regrowth after both early-dry season and early-wet season fires to promote perennial grass health during critical growth periods, ensure good grass cover, and protect soil during early-wet season rainfall.

Weed Management along River Frontage with Dispersive or Sodic Soils

The invasion of exotic weeds into river frontage country and riparian zones has become ubiquitous in the Normanby catchment (Plate 8). Many annual weeds compete with preferred native perennial grasses, provide little ground cover at the beginning of the wet season, have low root density and soil cohesion, and change the infiltration potential of soils. Most weeds have been introduced or increased in river frontage from upstream land use, local disturbance such as over-grazing, altered competition dynamics between grass and weeds, intense late-dry season fires, roads and fences. More scientific experimentation is needed on how to control weeds (fire, chemical, mechanical, biological) along river frontage terraces and elevated floodplains with sodic soils to promote perennial grass health, reduce water runoff and minimise gully erosion.

Plate 8 Invasion of annual weeds onto terraces (Hyptis, Hairy Sida, Grader Grass) and river benches (Sicklepod) in Normanby river frontage.

- *Draft BMPs for Weed Management along River Frontage with Dispersive or Sodic Soils*
  - Spell cattle from river frontage to increase grass competition with weeds.
  - Use grass fuel loads after spelling to periodically use fire at appropriate times/locations for weed control (e.g., rubber vine) and breaking weed seed cycles (e.g., hyptis, grader grass).
  - Use herbicides and other control methods in strategic areas to reduce weed cover.
  - Prevent spreading weeds along roads and fences. Clean vehicles/machines regularly.
  - Prevent spreading weeds with imported hay.

  - Prevent spreading weeds when moving cattle from weeded paddocks to less weeded areas, or between properties. Use holding paddocks with regular weed management to contain weed spread.

Road and Fence Placement on River Frontage with Dispersive or Sodic Soils

The best long-term solution to road and fence stability is to not locate this infrastructure on dispersive or sodic soils and river frontage areas (Plate 9; Plate 17). Once dispersive or sodic soils are disturbed, erosion is difficult to prevent. Roads and fences should be placed on stable soils and geology, such as on subtle ridge and spur crests between drainage catchments. Maps of soil/geology, topography (including LiDAR), erosion hazards, and aerial photographs (+Google Earth) can be useful for locating infrastructure during property planning and to minimise the number of crossings of existing gullies, unchannelled hollows, creeks, and rivers. This will reduce long-term road maintenance costs and rill and gully erosion. Where roads and fences must be located through erodible river frontage, frequent water diversion structures (whoa boys) should be installed and capped with locally imported soil/gravel, in addition to armouring the approaches to creek crossings to minimise gully erosion. Vegetation clearing should also be minimised, especially on steep banks.

Plate 9 Roads graded repetitively on river frontage with sodic soils can lead concentrated water flow and deep gully erosion.

- *Draft BMPs for Road & Fence Locations on River Frontage with Dispersive or Sodic Soils*
  - Avoid building roads and fences through river frontage with dispersive or sodic soils.
  - Locate roads and fences on stable soils and geology, such as on subtle ridge and spur crests between drainage catchments.
  - Minimise the number of road/fence crossings through unchannelled hollows, gullies, creeks, and rivers.
  - Scout and map the best routes for fences using motor bikes, GPS, topographic maps and Google Earth images. Adjust line accordingly to avoid erosion hazards.
  - Install frequent water diversion structures (whoa boys) capped with locally imported angular gravel, in addition to armouring the approaches to channel and hollow crossings.
  - Water diversion frequency depends on slope and soil type, but for highly erodible soils on slopes >5%, spacing should be every 10-25 metres.
  - Minimise vegetation clearing (grass and trees) especially on steep banks.

Vegetation Clearing along River Frontage with Dispersive or Sodic Soils

Tree clearing along river frontage can initiate or accelerate alluvial gully erosion by disturbing soil and vegetation from bulldozing, chaining, and stick raking vegetation, as well as changing the water balance by reducing water transpiration by trees, raising water tables, increasing sub-surface water seepage, and accelerate surface water runoff (Plate 10). Generally, clearing trees from dispersive soils on river terraces and floodplains of river frontage should be avoided. Where this has already occurred, mitigation measures can be instated to reduce the continuing or future erosion of alluvial gullies.

Plate 10 Clearing tree vegetation along river frontage can disturb dispersive soils and initiate or accelerate alluvial gully erosion.

- *Draft BMPs for Vegetation Clearing along River Frontage with Dispersive or Sodic Soils*
  - Avoid clearing trees and other vegetation along river frontage with dispersive or sodic soils.
  - Retain or install grass and tree vegetation buffers along with cattle exclusion along drainage lines, hollows, gullies, creeks and rivers, well back from breaks in slope of high banks
  - For small gullies and creeks, buffer widths should be > 50 m wide from the high banks where alluvial gullies often initiate.
  - For larger creeks and rivers, buffers should be > 100 m wide from the high banks to include the local catchment area of gullies and hollows.
  - In practise, uncleared buffers could be > 1 km from the centre of large creek or river channels (Plate 2).
  - Install contour banks on cleared paddocks to manage excess water runoff.
  - Install earthen banks around gully heads to divert water runoff into a safe disposal points.
  - Where tree regrowth after clearing is problematic, use cattle spelling, periodic fire, pasture competition, and chemical weed control to control regrowth, rather than repeated mechanical intervention that can disturb soils and accelerate erosion.

Direct Rehabilitation of Alluvial Gullies at the Local Scale

Direct gully rehabilitation of alluvial gullies on a site-by-site basis is applicable to strategic priority sites with significant human interest (roads, fences, dams, buildings, yards, key riparian paddocks, key waterholes, biodiversity hot spots, and/or cultural sites) where benefits to intervention outweigh the costs. Direct intervention is also applicable to young highly-active gullies in early development stages, where timely intervention is justified to prevent or slow future extreme erosion.

There are many bio-geo-engineering options available for direct intervention and rehabilitation of gullies, however most have not been well tested for alluvial gullies in northern Australia. Experimental trials in this report contribute to that research deficit, but ongoing research is needed to fully develop best management practices (BMPs). To reiterate, there are three main approaches to reduce the advance of existing gullies, which generally should be used in combination.

1. Reduce water runoff into and through gullies.
2. Stabilise gully headcuts and sidewalls with vegetation and physical structures.
3. Reduce the gully channel slope and increase roughness using structures and vegetation.

Water Diversion/Retention Banks above Gully Heads

Direct mechanical or engineering intervention to reduce water runoff patterns and volumes can be warranted in situations where the hillslope catchment is highly disturbed (e.g., agriculture fields) and where excess water runoff cannot be managed solely by increasing perennial vegetation cover (grass, trees, shrubs). Numerous types of water retention and diversion structures can be built, including contour banks for water retention, farm dams, and earthen water diversion banks immediately above gully headcuts, depending on the situation. Some structures such as contour banks are not appropriate for intact native grass woodlands. Others such as farm dams would be difficult to install and ineffective above lengthy fronts of alluvial gully head scarp. Water diversion banks above alluvial gully headcuts can reduce gully headcut erosion. However, they are also prone to failure by piping in dispersive sodic soils and can divert the erosion problem from one gully to another nearby making the erosion worse (Plate 11).

Plate 11 Water diversion banks above alluvial gullies can reduce erosion but also are prone to failure.

- *Draft BMPs for Diversion/Retention Banks above Gully Heads*
  - Construct contour berms in cleared paddocks only, or along roads and fences.
  - Divert excess runoff frequently and toward safe disposal areas armoured with rock. Avoid transferring the gully problem from one location to another.
  - For water diversion banks above gully heads in native grass woodlands, avoid disturbing native vegetation and dispersive or sodic soils where possible.
  - Use caution when using dispersive or sodic soils for diversion bank construction due to risk of soil piping and increased gully erosion.
  - Consider importing non-sodic soil or angular gravel from stable sites for diversion bank construction, rather than disturbing local dispersive or sodic soils.
  - Place banks far enough back from gully scarps to avoid damage by future gully retreat.

    - Use field observations of water flow paths and detailed topographic data (LiDAR) for bank design.
    - Use diversion banks in conjunction with gully revegetation, slope battering, gully grade control and cattle exclusion.

Increasing Perennial Grass Cover on Gully Slopes

Perennial grass cover is a key factor in stabilizing river banks, floodplain hollows and gullies. Reducing cattle grazing pressure along river frontage will help improve grass cover within and around potential and existing gully areas. However, once gully erosion has initiated and exposed nutrient poor sub-soils, natural revegetation can be slow. Experiments using native and exotic grasses to revegetate alluvial gully surfaces in the Normanby catchment have had mixed results. Grass seed sown directly on gully scarps, side walls, and excavated sub soils had poor germination success. Adding straw mulch and grass seed did not improve germination. Using a hydromulch mix (grass, gypsum, fertiliser, paper, bagasse, tackifier) on raw gully scarps in the wet season resulted in partial vegetation cover, concentrated in gully bottoms where moisture collected and sediment was trapped (Plate 12). More proactive revegetation efforts in association with soil amendments, slope battering, and grade control can be used to speed up vegetation recovery and promote gully stabilization.

Plate 12 Revegetation of gully scarps with hydromulch can result in modest but not complete cover improvements, while natural recolonisation can be successful with native grasses such as blady grass.

- *Draft BMPs for Increasing Perennial Grass Cover on Gully Slopes*
    - Fence cattle off from large areas of alluvial gullies and river frontage well back from high banks to allow perennial grass to grow, seed, recover, and compete with weeds.
    - Manage fire and weeds in river frontage to maximise perennial grass.
    - Hand or aerial seed grass vegetation in the wet season after initial heavy rains loosen the soils and provide prolonged soil moisture.
        - Focus grass revegetation efforts on gully toe-slopes and bottoms, in addition to areas immediately above gully scarps. Scarifying scalds and scarps may be needed for improved germination, but could temporarily increase erosion.
    - Revegetating gully scarps will have poor to moderate success unless intensive rehabilitation efforts are applied (e.g., slope battering, organic and chemical soil amendments, grass revegetation, cattle exclusion).

Intensive Rehabilitation of Gully Slopes

Both intact and battered alluvial gully slopes can be difficult to revegetate with perennial grass species due to the harsh nature of sodic, hard-setting soils with low nutrients and water availability. Importing non-sodic topsoil or capping sodic soils with rock and/or geotextile fabric – then revegetating with grass – can provide long-term stability. However, rock or good top-soil is not always available. Experimental results of intensive gully rehabilitation in the Normanby catchment indicate that physically regrading gullies, adding compost and gypsum, and revegetating with grass can reduce soil erosion compared to control sites with no soil amendments (Plate 13). In contrast, regrading gullies with machinery without soil amendments or where there is poor establishment of grass can actually increase gully erosion above previous levels. Using a full suite of treatments, erosion was reduced from >26.6 tonnes/year to 6.7 tonnes/year on a gully site that was battered and shaped into a hollow, amended with gypsum and hydromulch, and treated with wood grade control structures and a water diversion bank. This highlights that gully erosion can be reduced but not fully stopped even under intensive rehabilitation of a 0.2 ha gully for $6000.

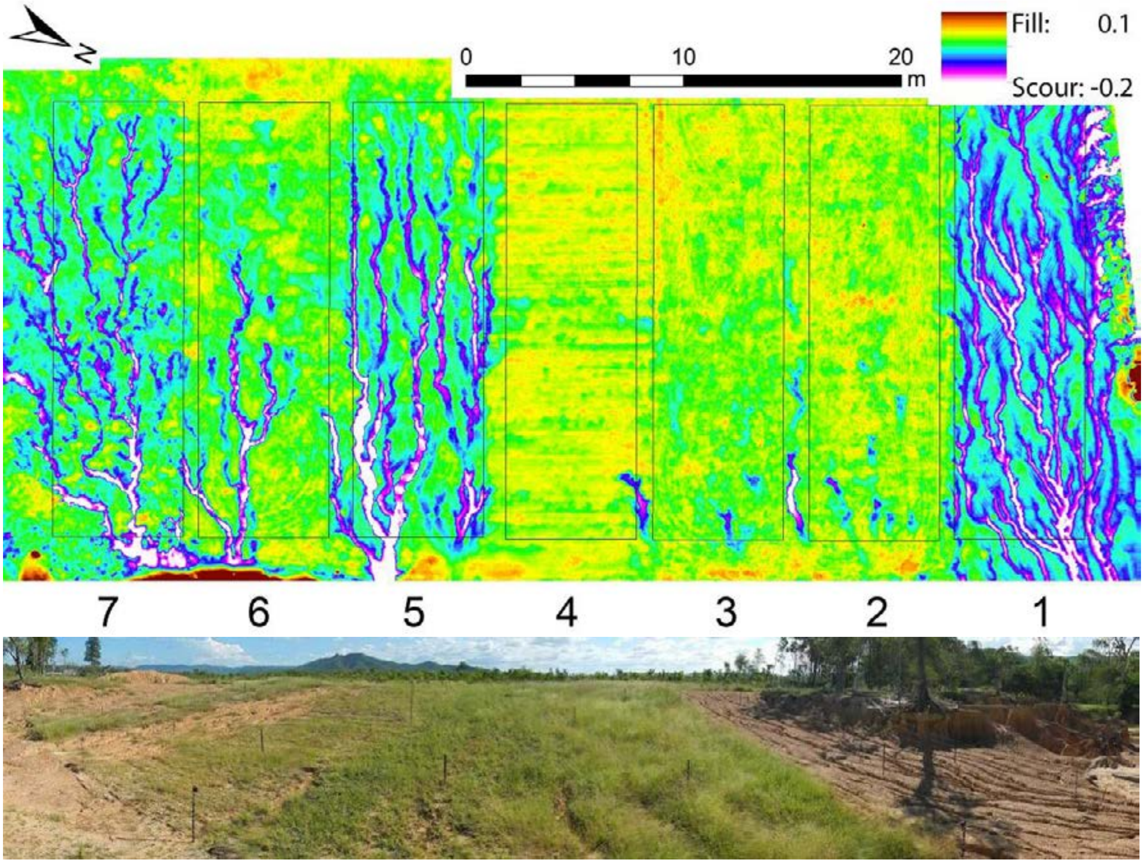

Plate 13 Differences in vegetative cover (below) and erosion changes (above) on battered gully slopes treated with different combinations of compost, straw, gypsum, and grass seed, and measured with terrestrial laser scanning (TLS) surveys in 2011 & 2013. Cattle were excluded via fencing. Control plot (1) is far right, full treatment plots (2-4) are centre, and partial treatment plots (5-7) are left.

- *Draft BMPs for Intensive Rehabilitation of Gully Slopes*
    - Do not batter (regrade) sodic gully slopes without revegetating and amending the soil, or capping with rock; they will re-erode into rills and gullies, accelerating erosion.
    - Where available, cap battered gullies with non-sodic topsoil or imported rock, then revegetate with perennial grass.
    - For rehabilitation of gully slopes in situ without imported soil or rock, batter (regrade) the gully into a stable shape and amend sodic soils with organic matter (compost or mulch), gypsum ($CaSO_4$), fertiliser, and perennial grass seed.
    - A combination of hydromulch for short-term erosion reduction and compost for long-term grass growth will provide the greatest erosion reduction benefit.
    - Install additional water diversion and grade control structures to reduce water runoff energy and local slopes.
    - Fence gullies to exclude cattle grazing from rehabilitation areas.

Grade Control and Headcut Drop Structures

Grade control and drop structures are applicable to narrow semi-confined gullies where overland flow dominates, but only some sections of unconfined alluvial gullies such as finger headcuts. Grade control structures (check dams) can prevent incision, reduce slope, dissipate energy, and trap sediment. Drop structures (weirs, chutes, flumes, etc.) installed at headcuts (scarps) can safely pass water runoff over the scarp edge and stop the gully headcut from advancing. These grade and drop structures can be made out of rock, gabion, concrete, sand bags, steel sheets or mesh, treated lumber, large woody debris (LWD), woven brush and/or live vegetation. Proper attention to engineering design, structure frequency, geomorphic processes, the stage or time of intervention, and long-term maintenance are essential for minimizing failure. Structures should be embedded into the underlying bed and adjacent banks to avoid undermining or outflanking, especially in dispersive soils. In the Normanby catchment, the placement of drop and grade structures is required at many young, very active headcuts advancing up floodplain hollows in river frontage areas in order to prevent major future erosion (Plate 14).

Plate 14 Young, rapidly advancing headcuts of alluvial gullies need to be stabilised with drop structures or rock grade control so that they do not develop into larger gullies and head scarps (Plate 1).

- *Draft BMPs for Grade Control and Headcut Drop Structures*
    - Grade control and drop structure are most applicable in young, linear gullies within semi-confined channels or valleys.
    - In large alluvial gully complexes, they are applicable to narrow finger headcuts and narrow outlets channels, but not wide gully bottoms or long scarp fronts.
    - Key (embed) grade control structures into bed and bank to prevent undermining and outflanking.
    - Use a size mixture of angular rock (or wood) to lock structures in place.
    - Avoid using loosely placed large boulders subject to piping through or around voids.
    - With drop structures at headcuts, use lateral and vertical cut-off walls to prevent water tunnelling around structures in dispersive soils. Install water seep holes through structures to prevent water pressure building up behind structures.
    - Monitor and maintain structures over time to ensure their longevity and functionality.
    - Minimise collateral damage from machine works on highly erodible soils.
    - Revegetate construction areas using perennial grass seed or hydromulch.
    - Do not use tyres or dump trash in gullies in an attempt at stabilization; this material will promote scour and accelerate erosion.

Road Erosion: Prevention and Repair on Dispersive or Sodic Soils

Improper road and fence location, construction and especially maintenance are major causes of gully initiation and acceleration on cattle station properties. They should be a major focus for intervention to reduce cumulative sediment yields. Avoiding highly erodible dispersive or sodic soils along river frontage and minimizing the number of crossings through hollows, creeks, and rivers where gullies initiate is key to prevention. For existing roads on dispersive or sodic soils, managing excess water runoff concentrating down roads and fences is key to erosion control. Large water diversion banks (whoa boys) installed frequently (every 10-25 m) down steep erodible slopes can reduce water concentration and gully erosion (Plate 15). However banks and road slopes must also be armoured with angular gravel or rock to prevent rilling and gullying of underlying sodic soils. Continuously regrading basic roads (Plate 9) or constructing large formed roads with mitre drains will accelerate gully erosion on fragile sodic soils. Rather, localised road erosion issues on sodic soils should be patched up each year following well-considered road maintenance plans and procedures.

Plate 15 Erosion on station roads over steep river banks in sodic soils can be reduced by installing frequent water diversion banks (whoa boys) and capping them with imported coarse rock.

- *Draft BMPs for Road Erosion Prevention and Repair on Dispersive or Sodic Soils*
    - Avoid and minimise road crossings though hollows, gullies, stream channels, and steep banks in dispersive or sodic soils.
    - Don’t grade down roads year after year resulting in entrenched roads without drainage.
    - Don’t regrade or fill in gullies on roads on steep banks each year just to gain immediate access. Address the actual cause of the gully erosion and manage water runoff.
    - Avoid continuously rerouting the road around erosion problem and ignoring them. Address the cause of the problem (excess water runoff).
    - When road abandonment is needed, address major water drainage issues with diversion banks and reseed with grass. Construct the new road to improved erosion control standards.
    - Bring past windrows from deep grading back onto the road surface, and use to crown the road surface and/or construct water diversion banks.
    - Reinstate the natural water flow direction (off the road) whenever possible.
    - On sodic soils, avoid constructing large formed roads with table and mitre drains, as disturbing fragile soils will accelerate gully erosion. Trying to overpower erosion problems with major machinery intervention can accelerate gully erosion on sodic soils.
    - Divert surface water runoff early along flow paths to prevent concentrated flow.
    - Install frequent, large water diversion banks (whoa boys) on top of the existing soil surface every 10 to 25m on highly erodible slopes >5%.
    - Construct high (>0.5m) and wide (5-10m) diversion banks to ensure long-term functionality and drivability.
    - Avoid diverting water into old gullies, toward creek/river banks and into hollows susceptible to gullying.
    - Where space is available on stable soils, dig a silt pond with sill outlet for diverting water into. Use the material to construct the bank (whoa boy).
    - Import angular gravel from stable local sources to armour steep road slopes and diversion banks at stream crossing approaches. Angular gravel/rock is preferred over river gravel, but both are better than native dispersive or sodic soils.
    - Seed disturbed areas with appropriate perennial grass species.
    - Develop annual road maintenance plans and procedures appropriate for dispersive or sodic soils. Annually patch up problem erosion areas and repair drainage structures. Allocate road maintenance budgets to proactively address problem areas, rather than let them develop into larger erosion problems that cost more in the long run.
    - Require grader/bulldozer drivers to attend workshops on erosion control.

Fence Erosion: Prevention and Repair on Dispersive or Sodic Soils

Fence lines can concentrate water and accelerate gully erosion when improperly placed, constructed, or maintained, in addition to when they are graded as fire breaks, used as roads, and cut by cattle tracks (pads). Proper fence placement around erodible soils can minimise future erosion and prolong the life of the fence. Best management practices to reduce gully erosion along fences include avoiding soil disturbance, using live trees as fence posts on steep banks, minimizing tree clearing and grass grading, installing water diversion banks armoured with gravel (Plate 16), and using prescribed fire, herbicides and/or slashers for fire breaks and vegetation management.

Plate 16 Installing frequent water diversion structures (whoa boys) along fences, and fencing tree-to-tree over steep banks with sodic soils, can reduce gully erosion along fences.

- *Draft BMPs for Fence Line Erosion Prevention and Repair on Dispersive or Sodic Soils*
  - Avoid and minimise fence line crossings though hollows, gullies, stream channels, and steep banks in dispersive or sodic soils.
  - Do not repeatedly grade fence lines as fire breaks and road access, as this will accelerate erosion.
  - Bring past windrows from deep grading back onto the fence line surface to avoid concentrating water, and use material to patch erosion areas and/or construct water diversion banks.
  - Install frequent, large water diversion banks (whoa boys) every 10 to 25 m depending on slope; manage surface water runoff to prevent concentrated flow.
  - Construct high (>0.5m) and wide (5-10m) diversion banks to ensure long-term functionality and prevent future machine operators from grading through them.
  - On steep slopes in erodible soil, armour water diversion banks with non-sodic soil/gravel to prevent cutting by rills and gullies. Use caution to not accelerate erosion during construction on steep erodible slopes.
  - Minimise the amount of tree and grass vegetation cleared and graded during fence installation and maintenance.
  - For fences down steep banks at crossings, use existing live trees as fence posts (tree-to-tree) to avoid the need for tree clearing and soil disturbance.
  - Use good fire management and variable early-dry season burning to control undesired fires.
  - If fencing must be used for fire breaks, use slashing and herbicides rather than grading fence lines and accelerating erosion. Maintain good grass cover in erosion sensitive areas.
  - Develop annual fence maintenance plans and procedures appropriate for dispersive or sodic soils. Annually patch up erosion hotspots, repair water diversion structures, and hand repair fences on steep banks and stream crossings. Require grader drivers to attend workshops on erosion control.

Social, Economic and Political Challenges to Alluvial Gully Rehabilitation

There are many social, economic, and political challenges to addressing alluvial gully erosion in the Normanby catchment on Cape York Peninsula. Motivational aspirations of graziers can range from strong ‘economic & financial’ to ‘stewardship & lifestyle’ motivations, which can influence conservation ethics and willingness to participate in and successfully complete government programs (e.g., Reef Rescue). Conservation funding programs need to be tailored to match and utilise these intrinsic motivations.

The grazing industry of the Normanby catchment and Cape York Peninsula is struggling economically and is in transition due to the long distance to markets, the extreme wet-dry climate, low soil productivity, land degradation from erosion and weed invasion, increased fixed and variable costs (e.g., rates, labour, fuel, material, feed), stagnant cattle prices, and increased debt levels associated with development and competition pressures. The result is little to no extra income or time to reinvest in long-term property management or soil conservation actions such as gully erosion control.

The total cost (commercial retail) of intensive gully treatments conducted in this study ranged from \$3000 to \$6000 for 0.2 ha, which included heavy equipment hire and labour, gypsum, hydromulch or compost, and fencing. Using local labour, machinery, and materials from individual properties might be able to reduce this to \$2000 for 0.2 ha. This equates to \$10,000 to \$30,000 per hectare for intensive gully treatment, which is well above the average costs of grazing properties in the Normanby catchment (< \$100 per ha). This direct intervention is most applicable where key infrastructure is threatened (e.g., roads, fences, yards, buildings, dams, key waterholes) or where young, incipient gullies can be stopped to prevent major future erosion and land loss. Direct intervention during this project was able to reduce gully erosion for \$375 per tonne, which is less than the average sediment erosion abatement cost of \$600/tonne paid by the Reef Rescue program. To reduce the estimated 736,400 tonnes per year eroded from alluvial gullies by 10%, it would cost \$27,600,000 at \$375 per tonne. Or alternatively, if 2000 ha of mapped gully in the catchment was treated with intensive intervention at \$2000 per 0.2 ha, it would cost \$20,000,000. Investing this level of government or market-based funding in the Normanby catchment might be better spent on purchasing large areas of degraded river frontage on specific cattle properties, and taking them out of cattle production as ‘soil conservation areas’ (Plate 5; Plate 17).

A fundamental paradigm shift in government policy and investment targets is needed to reduce gully erosion and sediment yields. Current cost-share programs are not achieving water quality improvements at the catchment scale in the Normanby catchment. Land management investments for erosion prevention and control should be driven by a holistic, long-term, process-based catchment-wide perspective, rather than relying on small, discrete, short-term projects with questionable benefits that treat symptoms rather than causes or only promote property development.

Targeted investment for gully erosion control at large mapped ‘hot spots’ (i.e., dispersive sodic soils on river terraces and adjacent floodplains) is needed using large-scale land management changes and localised intensive rehabilitation actions. Several priority river frontage areas for large-scale erosion management actions – such as cattle destocking to create soil conservation areas – have been identified in the Normanby catchment (e.g., the Granite Normanby River, Plate 5; Plate 17). Funding for large-scale actions could come from government investment for public benefit, market-based solutions (payment for ecosystem services of carbon, biodiversity, soil retention), and/or land utilization/tenure trading to destock cattle from highly erodible soils and develop more productive, less erosion prone soils for agricultural and economic benefit. However, government or market-based investments for combined carbon sequestration, biodiversity improvement, and soil conservation must pass the 'integrity' test by going beyond normal practice, be measurable and rigorously monitored, and be subject to peer review.

In addition to large targeted investments and incentives, a renewed emphasis should be placed on extension of knowledge, training, and certification programs that are founded within locally-based and long-term government funded programs [e.g., a reinstated Soil Conservation Service (SCS), Primary Industries, Landcare, Natural Resource Management (NRM) agencies]. These programs should focus on integrated property planning for erosion reduction and control and monitoring of results. Machine-operator certification programs (e.g., roads and fences) should be prerequisites for government funding for erosion control. The design, implementation, maintenance, and monitoring of more complicated gully erosion control projects might be best conducted by a team of qualified experts and practitioners (e.g., a reinstated Soil Conservation Service and geomorphologists).

For the Normanby catchment and Cape York Peninsula, a mixture of larger positive incentives and investments, extension and outreach, and long-term soil conservation programs will be needed to cumulatively reduce erosion at the catchment scale.

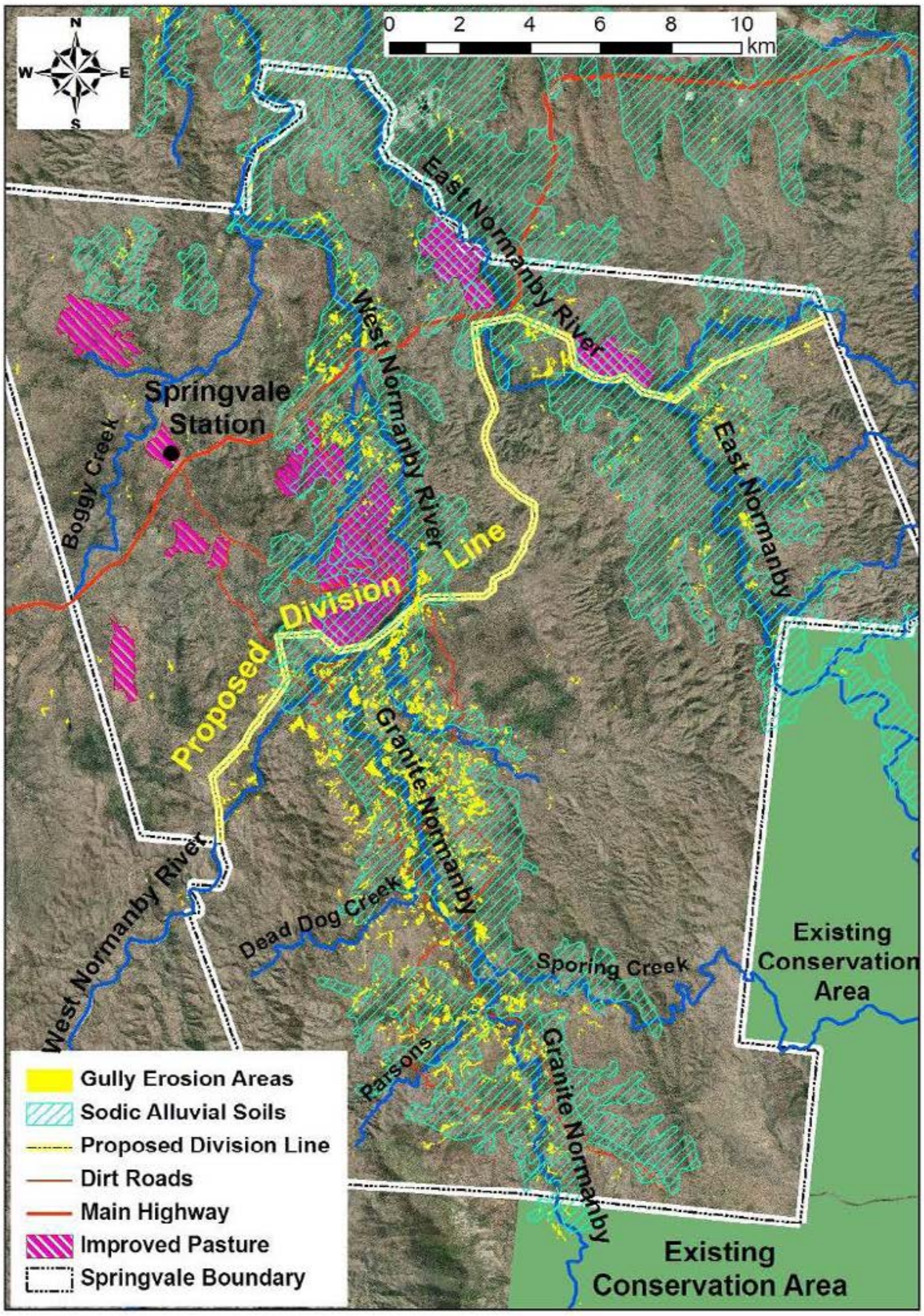

Plate 17 A DRAFT PROPOSED 'soil conservation area' - focused on the Granite Normanby River - where the highest concentration of alluvial gullies exists in the entire Normanby catchment. Note that existing 'improved paddocks' would stay under production and major monetary compensation would need to be provided to the lease holder for economic loss.

Future Research Priorities

Natural Vegetation Recovery Within and Above Alluvial Gullies

- The natural vegetation recovery potential within alluvial gullies and vegetation influences on reducing alluvial gully erosion are major topics for long-term research. Short-term cattle exclusion experiments cannot answer critical long-term recovery unknowns. The installation of small cattle exclusion experiments and direct revegetation conducted in this study are significant steps towards this research; however funding is needed for their continuation and expansion to larger land management units.
- 'Soil conservation areas' in high risk areas for alluvial gully erosion could be utilised as research stations to monitor large-scale, long-term experiments in savanna rangeland and gully erosion rehabilitation, using various gully, vegetation, fire, grazing and soil management regimes. These areas could also be conjunctively used for biodiversity improvements, carbon retention, and prevention of weed spread.

Proactive Revegetation Within and Above Alluvial Gullies

- Experimentation into large-scale aerial seeding grass vegetation into alluvial gullies during the wet season with a variety of plant species is needed before catchment-scale programs could be developed to cumulatively address gully erosion.
- The germination and growth success of a wider variety of native and exotic grass should be researched in sodic alluvial soils to determine the most appropriate species for seeding and stabilising gullies. The rooting depths and soil cohesion properties of native and exotic species also is poorly understood in sodic alluvial soils.
- The influence of annual weeds (herbs and grass) on the recovery of native perennial grasses, soil hydrological functions (infiltration, root cohesion, roughness), and accelerated water runoff from river frontage terraces need more research, in relation to downslope alluvial gully erosion.

Cattle Management and Alluvial Gullies

- Large-scale adaptive management research is needed on how to best balance the needs of cattle grazing, perennial grass health and cover, weed control, and fire management, while also reducing alluvial gully erosion on sodic soils and river frontage. Different cattle spelling and rotation regimes should be trailed to maximise vegetative cover in and around alluvial gullies while also supporting a viable cattle industry. Otherwise, cattle grazing pressure will need to be shifted away from large areas sensitive to gully erosion.
- The mechanisms of gully initiation and acceleration from cattle tracks (pads) needs more research. Studies should be conducted on animal migration routes and patterns via tracking, vegetation cover influenced by grazing along tracks, water runoff acceleration along tracks, subtle water flow paths across floodplain flats and hollows, cattle track concentration down pre-existing gully features, and the potential to revegetate and infill existing cattle tracks over time through cattle exclusion.

Fire Regimes and Alluvial Gullies

- Fire regimes research should be conducted to determine what specific fire regimes would be most appropriate to reduce water runoff, soil erosion, and the initiation or acceleration of alluvial gully erosion on river frontage woodlands and grasslands in northern Australia, especially on highly dispersive or sodic soils on alluvial terraces and floodplains. Research on the use of fire for weed control along river frontage terraces is also needed. Sediment erosion and yield should be measured in association with careful fire treatments and control sites.

Physical Control of Alluvial Gullies

- Headcut stabilisation field experiments are needed for controlling young very active headcuts of alluvial gullies using engineered chute and drop structures, especially in dispersive or sodic soils. Their physical- and cost-effectiveness, long-term stability, and geomorphic impacts are unknown for alluvial gullies.
- The use of water diversion berms above long alluvial scarp fronts should be researched and trialled in more detail. Careful consideration is warranted for disturbance of sodic soils, damage to native vegetation, flow paths on subtle topography, designing safe water disposal areas, future scarp retreat, and piping through berms in sodic soils.
- Road field experiments are needed on how to best install, manage and maintain simple dirt roads and tracks in highly dispersive or sodic soils and steep river banks on river frontage in northern Australia, in order to reduce alluvial gully erosion initiation and acceleration. Road research started in this study should be continued to understand longer-term declines in sediment yield from roads treated with preliminary BMP structures and surfacing.

Social-Economic Aspects of Alluvial Gully Control

- The costs and economic viability of alluvial gully erosion control measures needs more detailed research and guidance, with and without government or market-based assistance.
- The market potential for payments for ecosystem services (soil, carbon, biodiversity retention) to reduce alluvial gully erosion should be investigated in detail.
- The economic value of losses of sediment, riparian habitat, biodiversity, and carbon sequestration potential along river frontage needs to be quantified, as well as off-site impacts of alluvial gully erosion on downstream sedimentation, freshwater and marine habitat degradation, and cultural use and values across the landscape.
- The profitability of marginal and degraded grazing lands on Cape York Peninsula needs research attention, along with the economic and social costs of improving water quality by altering land use, and the economic benefits of soil retention to grazing and farm production.

Summary Key Issues

- Gully erosion is likely the dominant *accelerated* erosion process across the whole of northern Australia and the GBR catchments contributing to elevated river sediment loads.
- To date there have been few effective management strategies employed that are targeting and addressing this problem.
- Current models of delivering NRM funding are not effectively dealing with major concentrated areas of gully erosion, nor effectively reducing sediment yields.
- By default the management of gully erosion issues has been left almost entirely up to cattle graziers – with minimal effective assistance from government programs.
- Given the poor economic state of Cape York Peninsula cattle industry at present, cattle graziers have little capacity to properly address this problem. As such the problem persists unchecked or accelerated under current paradigms.
- With the predicted expansion of grazing intensity, mining and agriculture in northern Australia, the gully erosion problem will continue to increase if left unchecked (if nothing else through the expansion of the road network and growth of existing gullies).
- A completely new approach and scale are required to address gully erosion if any real progress is to be made towards reducing sediment yields from rangeland grazing country, which is the primary source for sediment pollution to local river systems in northern Australia and the GBR.

Summary Key Actions

- Large concentrated areas of mapped alluvial gully erosion with high erosion risk should be targeted for erosion reduction measures using large-scale land management changes (cattle, fire, weed, roads, fences) and localised intensive rehabilitation actions.
- Cattle grazing pressures need to be shifted away from river frontage areas with dispersive or sodic soils prone to alluvial gully erosion.
- A joint Federal/State/Territory partnership with key industries (cattle, mining, tourism and irrigated agriculture) is needed to re-establish a northern Australia or Queensland 'Soil Conservation Service'. The renewed SCS should have the specific purpose of developing the scientific, extension and application services required to address widespread soil and gully erosion with large-scale land management changes and localised intensive rehabilitation actions.
- Integrated, multidisciplinary property planning is needed to help shift grazing away from sensitive areas of high erosion risk, as well as help landowners (pastoral, agricultural, Indigenous) on Cape York Peninsula with improved land management, stock/pasture/crop management, and financial management.
- Once integrated property plans are developed, landowners assistance with action implementation and monitoring will be needed to adaptively manage perennial grass cover, weeds, fire, roads, fences, and erosion control measures.

Acknowledgements

This project was funded by the Australian Government's Caring for our Country - Reef Rescue Initiative. Project management support was provided by Cape York Sustainable Futures (CYSF). We would like to thank Isha Segboer, Peter Thompson, Laura Richardson and Trish Butler for their collaboration. Special thanks also go to Ian, Malcolm and Lynette McCollum of the former Cape York Marine Advisory Group (CYMAG) for their project and personal support over the years.

This project would not have been possible without local graziers in the upper Laura-Normanby catchment who supported this research towards a deeper understanding of 'breakaways' and their management. We thank Roy and Karlene Shepard and Johnny Ross from Crocodile Station for their open invitation, project assistance, property dedication, and willingness to share erosion management thoughts. We thank Damian Curr, Bridget Adams, and Luke Quaid from Springvale Station for their hard work and forthright conversations about the difficulties and scale of managing severe gully erosion. Daryl and Lynda Paradise from Kings Plain Station, Harrigan family from Normanby Station, Bill Bambury from Olive Vale Station, and Bill Reddie from Turalba Valley also provided welcome advice and fruitful conversations.

We acknowledge the Aboriginal Traditional Owners of the country where this research took place. Specifically on Crocodile Station, we thank the following family groups among others: Tayley/Gibson/Ryan/Banjo/Donald/Chookie/Simon/Costello/Cummins/Brady/Rosendale/Ross/ Snider. On Springvale Station near the Granite/East/West Normanby, we thank the McClean family and others (Dyugunwarra) and the Gibson/Hamett families and others (Bulganwarra). For the Normanby Station area, we thank the Harrigan family and others. The Western Yalanji and Ang Gnarra Corporations and Professor Bruce Rigsby (University of Queensland) provided logistical advice for navigating traditional country.

Materials, machinery and labour for the project were provided by Far North Earthmoving, Mo and Tanya Jenkins Earthmoving, Mario Puccini Excavations, Swiss Farms, Miriwinni Lime, Tony Illing Seeds, Native Seeds, Revegetation Contractors, Jones Mobile Crushing, Oz Earthmoving, and Tom and Chris Besant Fencing. Special thanks go to Annette and Peter Marriott for their local guidance and open conversations.

Field support was provided by Lucas Armstrong, Brad Guy, Christina Howley, Jason Carroll, Angela Gleeson, Zoe Lieb, Amanda Hogbin, and John Spencer, in addition to Lachlan Young and Nat Ferraro from RPS Group Plc. Writing support was provided by Jean Stephan, Christina Howley, and Kim Stephan.

Technical and laboratory support for the project were graciously provided by John Spencer, Tim Pietsch, Daniel Borombovits, Graeme Curwen, Rawaa Abdul Jabbar, Bahar Nader Al-Uzairy, and Scott Byrnes at Griffith University. Nick McKelvey, Lachlan Young and Nat Ferraro from RPS provided terrestrial laser scanning (TLS) support. David Moore from Terranean Mapping Technologies/RPS provided airborne LiDAR support. Gerry Turpin and Darren Crayn from the Australian Tropical Herbarium assisted with plant identification.

Graham Lancaster and Kris Saville from Environmental Analysis Laboratory assisted with soil, straw, and compost analysis.

Natural resource management (NRM) advice was provided by Isha Segboer and Peter Thompson (CYSF), Joe Rolfe (QDAFF), Jason Carroll (SCYC), Ted Lee and Sue Marsh (Laura Rangers), Andrew Hartwig (Landcare), Ian McCollum (CYMAG), Brynn Mathews (MRWMG), Darryl Hill (Soil Save), Mark Silburn (QDNRM), Andrew Biggs (QDNRM), Bruce Carey (QDSITIA), Janie White (QPWS), Keith MacDonald (former QPWS), Gabriel Crowley (Firescape Science), John Colless (Wetherby Station), Annette and Peter Marriott (Far North Earthmoving), Mo Jenkins (M&T Jenkins Earthmoving), Leigh Vohland (Oz Earthmoving), Luke Quaid (Springvale), Daryl Paradise (Kings Plain), Roy Shepard (Crocodile).

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List of Acronyms

AGSO – Australian Geological Survey Organisation

BFM – Bonded Fibre Matrix

BMP – Best Management Practice

BOM – Bureau of Meteorology

BOS – Break-of-Season

CSIRO – Commonwealth Scientific and Industrial Research Organisation

CYMAG – Cape York Marine Advisory Group

CYSF – Cape York Sustainable Futures

CYPLUS – Cape York Peninsula Land Use Strategy

DEM – Digital Elevation Model

EMP Exchangeable Magnesium Percentage

ESP Exchangeable Sodium Percentage

LWD – Large Woody Debris

LiDAR – Light Detection and Ranging

MRWMG – Mitchell River Watershed Management Group

NAFI – Northern Australia Fire Information

NRM – Natural Resource Management

OSL – Optical Stimulated Luminescence

PAM – Polyacrylamide

PSD – Polysaccharide

QDAFF – Queensland Department of Agriculture, Fisheries and Forestry

QDEEDI – Queensland Department of Employment, Economic Development and Innovation

QDERM – Queensland Department of Environment and Natural Resource Management

QDSITIA – Queensland Department of Science, Information Technology, Innovation and Arts

QDPIF – Queensland Department of Primary Industries and Fisheries

QPWS – Queensland Parks and Wildlife Service

SCS – Soil Conservation Service

SCYC – South Cape York Catchments

SOC – Soil Organic Carbon

TLS – Terrestrial Laser Scanning

WY – Water Year

1 Introduction

Gully erosion is the process by which running water cuts new unstable channels into erodible soil and weathered rock. In northern Australia there is widespread alluvial gully erosion (*sensu* Brooks et al. 2009; Figure 1) into unconfined alluvial deposits on elevated floodplains and terraces (relict floodplains) adjacent to rivers and creeks with highly dispersive or sodic soils (Table 1; Figure 5). Alluvial gully erosion scarps are locally known as "breakaways" by pastoralists (Figure 1).

Figure 1 Typical alluvial gully "breakaways" in the Normanby catchment migrating away from a river channel and consuming the floodplain/terrace savanna landscape of the river frontage.

Alluvial gully erosion is both a natural and human land use accelerated erosion process (AGSO 1995; Brooks et al. 2009; Shellberg et al. 2010; Shellberg 2011; Shellberg et al. 2013a; Shellberg et al. 2013b). These alluvial gullies or 'breakaways' initiate on the steep banks of rivers and creeks and erode into elevated floodplains and terraces previously created by river deposits (Figure 2). River incision over geologic time, highly erodible soils, and an intense monsoon climate are natural factors priming the floodplain landscape for alluvial gully erosion. Most alluvial gullies erode into highly dispersive or sodic soils (Sodosols) along river frontage. Natural disturbances from heavy rainfall, flooding, drought, and fire in isolation or combination can trigger or propagate gully erosion. Human land use can play a major role in triggering or accelerating alluvial gully erosion. Examples of this are cattle grazing, cattle tracks (pads), fires, roads, fence lines, agricultural clearing and production, dam construction, and infrastructure development (AGSO 1995; Shellberg et al. 2010; Shellberg 2011; this report). Once triggered by natural and/or land uses factors, alluvial gullies can aggressively consume river floodplain and terraces. In many northern Australian catchments, sub-surface sediment derived from gullies (alluvial and colluvial) and bank erosion (small and large channels) dominates the total load of suspended sediment, in contrast to sediment from the surface of hillslopes (Wasson et al. 2002; 2010; Rustomji et al. 2010; Shellberg 2011; Caitcheon et al. 2012; Brooks et al. 2013; Wilkinson et al. 2013; Olley et al. 2013).

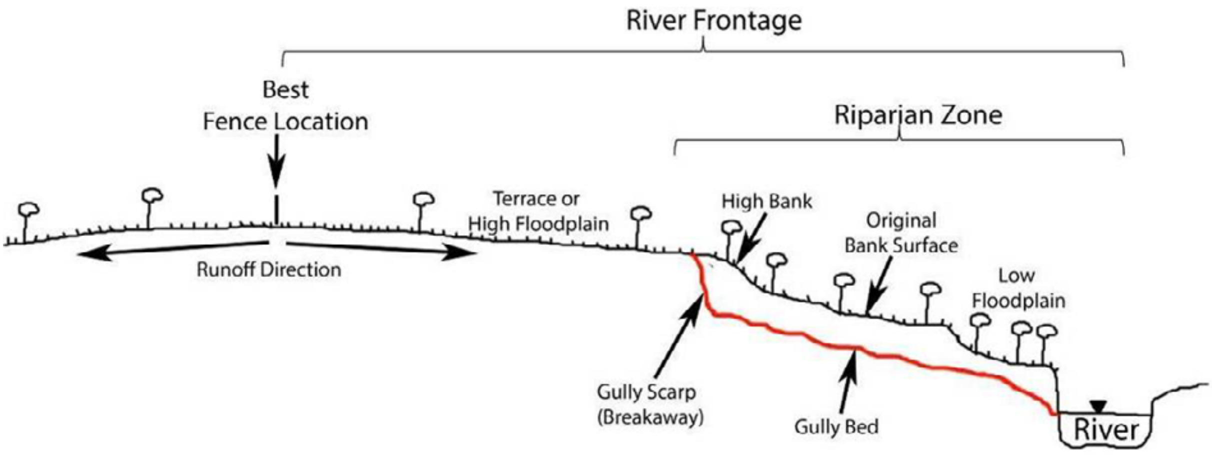


Figure 2 Cross-section drawing of an alluvial gully (bed and scarp) eroding into a high floodplain or terrace catchment from a steep river bank along the river frontage and riparian zone.

The erosion of floodplain soils via alluvial gully erosion presents major local and cumulative threats to: 1) the local pastoral industry through the loss of productive riparian land, 2) existing human infrastructure (e.g., roads, fences, buildings, and water points), 3) future potential agricultural development, 4) downstream aquatic ecosystems influenced by elevated sediment yields, associated nutrients, and habitat changes from sedimentation (i.e., river pools; lagoons, wetlands, estuaries, costal margins, coral reefs), 5) indigenous cultural use of water bodies for subsistence, commercial, and ceremonial purposes (i.e., fisheries production), and 6) the long-term sustainability of the landscape and provision of ecosystem services.

Consultation with landowners, managers, and Traditional Owners in the Normanby and Mitchell catchments in northern Queensland indicates that there are significant concerns about alluvial gully erosion and many unknowns surrounding how it should be managed. Due to the unique nature of alluvial gullies in northern Australia compared to colluvial or hillslope gullies in SE Australia, it became clear that on-the-ground trials starting at the basics were needed to initiate the regional development of rehabilitation options and best management practices (BMPs) applicable across the alluvial landscape of northern Australia

The main goals of this report and the project in the Normanby catchment were to:

1) Review the current scientific knowledge on alluvial gully erosion as related to natural and human accelerated factors, processes, and rates,
2) Review literature on gully prevention, rehabilitation, and best management practice options applicable to alluvial gullies in northern Australia,
3) Implement several field trials and experiments for preventing and rehabilitating alluvial gullies in the Normanby catchment, and assess their physical and cost effectiveness,
4) Provide information useful toward the *future development* of a comprehensive regional Best Management Practice (BMP) manual to address alluvial gully erosion across northern Australia.

A separate on-the-ground works program (Reef Rescue cost-share) was initiated with local landowners to implement sustainable grazing practices around riparian zones and alluvial gullies near water bodies across the catchment. The secondary goals of both projects were to:

5) Educate the local and wider pastoral community about gully rehabilitation techniques, successes and failures, and other management options,
6) Highlight some of the economic, social, and physical obstacles to reducing gully erosion locally and at the catchment scale to minimise the cumulative effects of land use change.

These concepts summarised in this report thus support the overall goal to cumulatively reduce local erosion and downstream delivery of sediment and nutrients to receiving water such as mainstem rivers, wetlands, estuaries, coastal margins, and off-shore coral reef environments. Reducing sediment erosion and yield to these downstream waterways will not be achieved unless the complicated natural and land use factors associated with alluvial (and colluvial) gully erosion are addressed via management and rehabilitation actions implemented cumulatively at the catchment scale (Bartley et al. 2010a; 2010b; Rustomji et al. 2010; Shellberg 2011; Caitcheon et al. 2012; Brooks et al. 2013; Wilkinson et al. 2013).

2 Background to Alluvial Gully Erosion in Northern Australia

2.1 Differences Between Alluvial and Colluvial (Hillslope) Gullies

Colluvial or hillslope gullies typically found on the tablelands and mid-slopes of coastal south-eastern Australia (Crouch 1990) and northern Australia (Hancock and Evans 2006) have dominated research about gully erosion processes and rehabilitation management in Australia. Hillslope gullies typically erode into colluvium (i.e., accumulated rock and soil at the base of hillslopes from long-term gravitational processes and overland flow), but this colluvium can also be mixed with some minor alluvium (i.e., sediment transported, abraded, and sorted by flowing water in channels). Hillslope or colluvial gullies tend to be fairly linear erosional features, where their lateral and vertical erosion is confined by bedrock and their upslope migration tends to be self-limiting as a function of the catchment area, slope, and the availability of colluvium to erode (Figure 3a). Hillslope gullies are not always directly connected to the downstream channel network, with the eroded sediment deposited in a "floodout" or small fan deposit (Erskine and Melville 1984). Under these circumstances their contribution to the river sediment loads is significantly less than if they were fully connected to the drainage network.

Alluvial or floodplain gullies originate at steep stream banks and erode into adjacent, relatively flat, alluvial floodplains and terraces (Figure 2; Figure 3b). Alluvial gullies have been inconsistently described in the international literature as bank gullies, ravines, valley-bottom gullies, and alluvial breakaways from locations around the world (Brooks et al. 2009; Shellberg 2011; Shellberg 2013a; Shellberg 2013b). Due to a lack of bedrock confinement, alluvial gullies are often as wide as they are long and expand longitudinally and laterally until they develop new equilibrium channel slopes and consume massive volumes of floodplain alluvium. This alluvial material tends to be much finer sediment than most colluvial deposits, thereby contributing a higher proportion of fine sediment to river suspended sediment loads. They are also highly connected to the stream network, delivering their sediment load directly to the main channel.

The difference between alluvial and colluvial gully types is important because the factors controlling their initiation, progression and ultimate stabilization differ substantially.

While there is a long history of attempting to manage and control colluvial/hillslope gullies in south-eastern Australia, often unsuccessfully, scientists and managers are only just beginning to address managing these far more extreme alluvial/floodplain gullies that are found across northern Australia. **It is clear that directly importing management approaches from hillslope gullies in southern Australia is unlikely to provide a solution to managing alluvial gullies in northern Australia, although there is much that can be learnt from past successful and unsuccessful experiences.**

a) b)

Figure 3 Examples of a) a tropical hillslope/colluvial gully that is elongate and eroding into relatively coarse colluvial material in the lower part of a hillslope, and b) a tropical alluvial gully eroding into deep alluvial deposits that is expanding laterally as well as longitudinally.

2.2 Types and Forms of Alluvial Gully Erosion

From field research and remote sensing mapping across northern Australia, it is clear that alluvial gullies eroding into floodplain systems come in a variety of forms depending on local processes (Condon 1986; Brooks et a. 2006; 2007; 2009; 2012; McCloskey 2010; Shellberg 2011). Most alluvial gullies drain directly into main channels (*proximal* gullies), while some gullies drain away from the main channel towards distally draining creeks or lagoons (*distal* gullies). Often both *distal* and *proximal* gullies will be found at a single location, consuming the floodplain from both directions. In planform (Figure 4), *linear* alluvial gullies are often young incipient gullies, commonly associated with land-use disturbances such as stock tracks, roads, and fences that tend to concentrate overland flow. *Dendritic* gullies are associated with well-defined drainage networks, separated by distinct interfluves with often less distinct or continuous head scarps. *Amphitheatre* gullies are often as wide as or wider than they are long due to the lack of structural control, and have well developed head scarps that drain into relatively narrow outlet channels. *Continuous scarp front* gullies are mature in phase, located parallel with main channels, and develop from the coalescence of numerous laterally expanding amphitheatre gullies and/or from river bank erosion on meander bends.

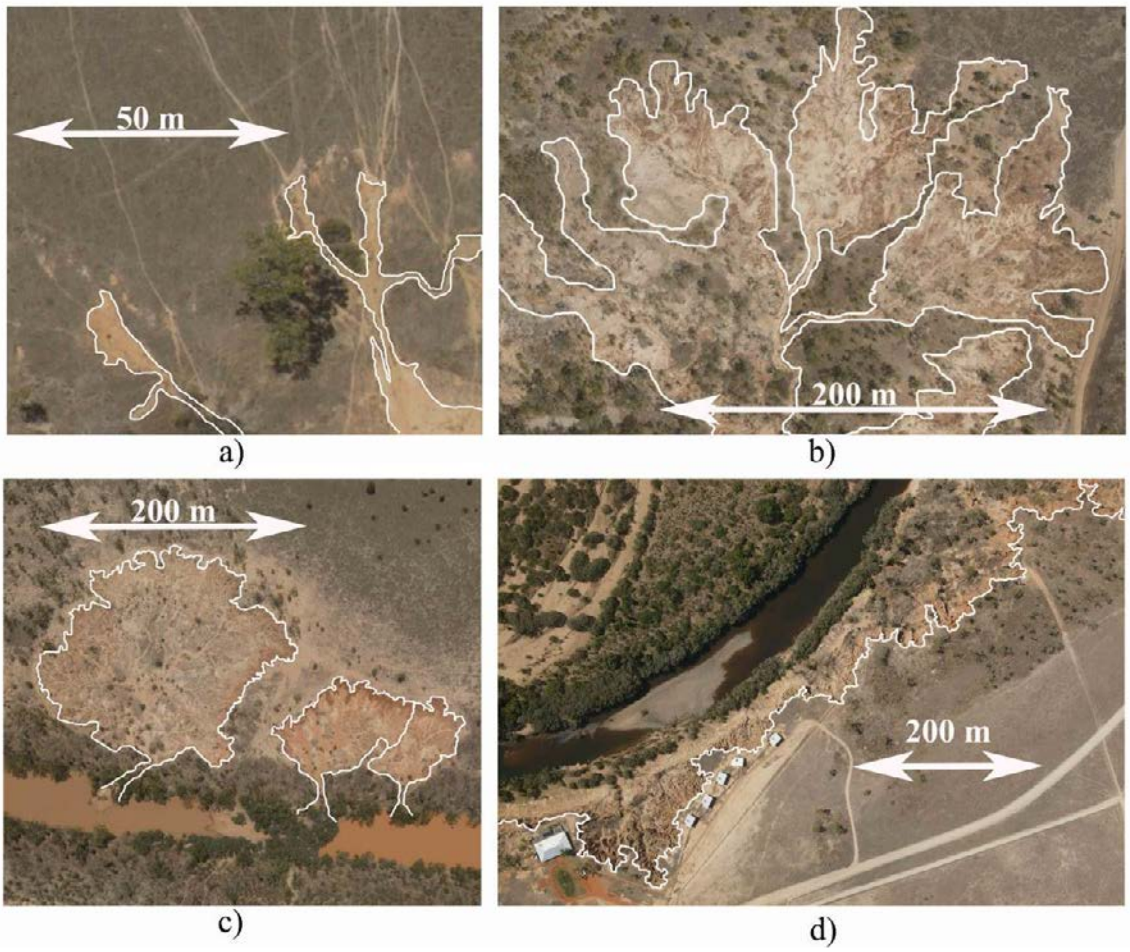


Figure 4 Examples of different planform morphologies of alluvial gullies: a) linear; b) dendritic; c) amphitheatre; d) continuous scarp front (Brooks et al. 2009).

2.3 Distribution of Alluvial Gullies Across Northern Australia

Alluvial gullies are widely distributed across floodplain environments of northern Australia (Table 1; Figure 5). However, they are not restricted to the tropics and exist in other locations across the continent and world (Brooks et al. 2009; Shellberg 2011; Shellberg 2013a; Shellberg 2013b). In Queensland, satellite, aerial photo, and remote sensing data have been used to document and map extensive areas of floodplains degraded by active alluvial gully erosion in many catchments (Table 1). These estimates are based on the mapping of bare, de-vegetated surfaces eroded by alluvial gullies (Brooks et al. 2006; 2007; 2008; 2009; 2013; Knight et al. 2007). They are a minimum due to vegetation masking of gullies under tree canopy. For example, in the Normanby catchment the true alluvial gully area is 7.6 times the bare area estimated from aerial photos (Brooks et al. 2013). However these conservative mapped estimates (Table 1) still can cover up to 1.0 % of the total catchment area and locally >10% of the floodplain area. Similar *alluvial* gully erosion extents have been estimated in the Victoria (NT, 811, Condon 1986; 1988; McCloskey 2010.) and Fitzroy (WA, 802, Payne et al. 1979) catchments (Table 1). Alluvial gullies also have been studied in the Daly (NT, 814, Sattar 2012), Ord (WA, 809, Medcalff, F.G., 1944) and Fitzroy (QLD, 130, Skinner et al. 1972) catchments, and observed in the Flinders (QLD, 915), Norman (QLD, 916), Staaten (QLD, 918), Coleman (QLD, 920), Stewart (QLD, 104), and Burdekin (QLD, 120) catchments. They likely exist along additional floodplain rivers in the Australian tropics.

Table 1 Estimated minimum area of alluvial gullies in different catchments.

Catchment	**Basin Number (Code) Figure 5**	**Bare Ground Minimum Area of Active Alluvial Gullies (ha)**	**% Catchment Area**
Normanby (QLD)	105	2,031	0.08%
Mitchell (QLD)	919	16,700	0.23%
Gilbert (QLD)	917	10,100	0.22%
Leichhardt (QLD)	913	29,100	0.87%
Gregory/Nicholson (QLD)	912	12,300	0.24%
Victoria (NT)	811	10,400	0.22%
Fitzroy (WA)	802	36,300	0.39%

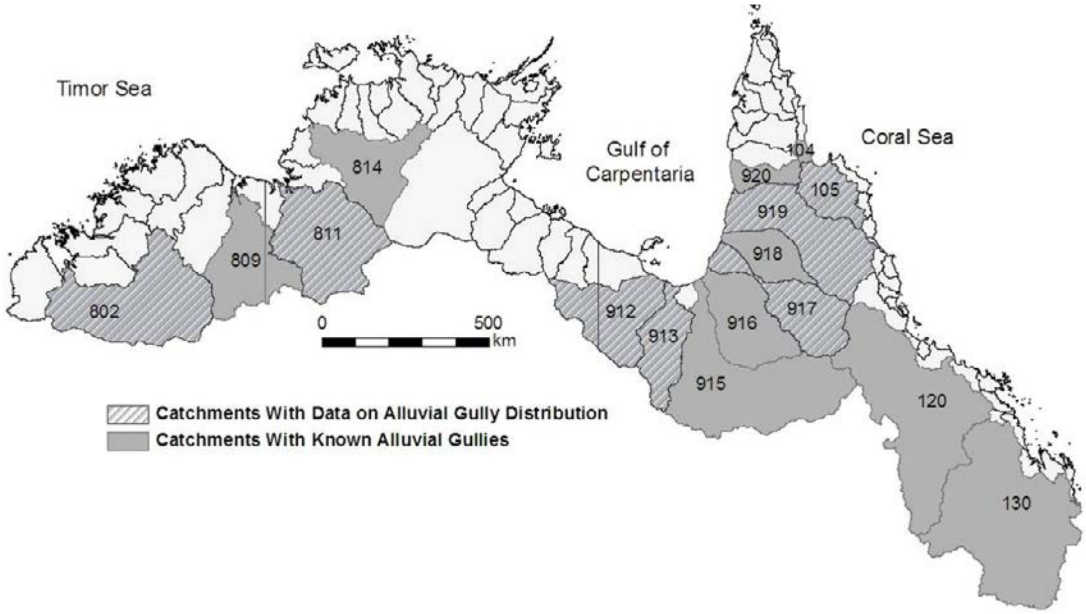


Figure 5 Map of catchments in northern Australia that either a) have data on alluvial gully distribution (stipple) or b) have known alluvial gullies that have not been quantified or mapped circa 2012 (dark grey). Catchment basin-numbers are included on the map, the text, and in Table 1.

2.4 Natural Factors Influencing Alluvial Gully Erosion

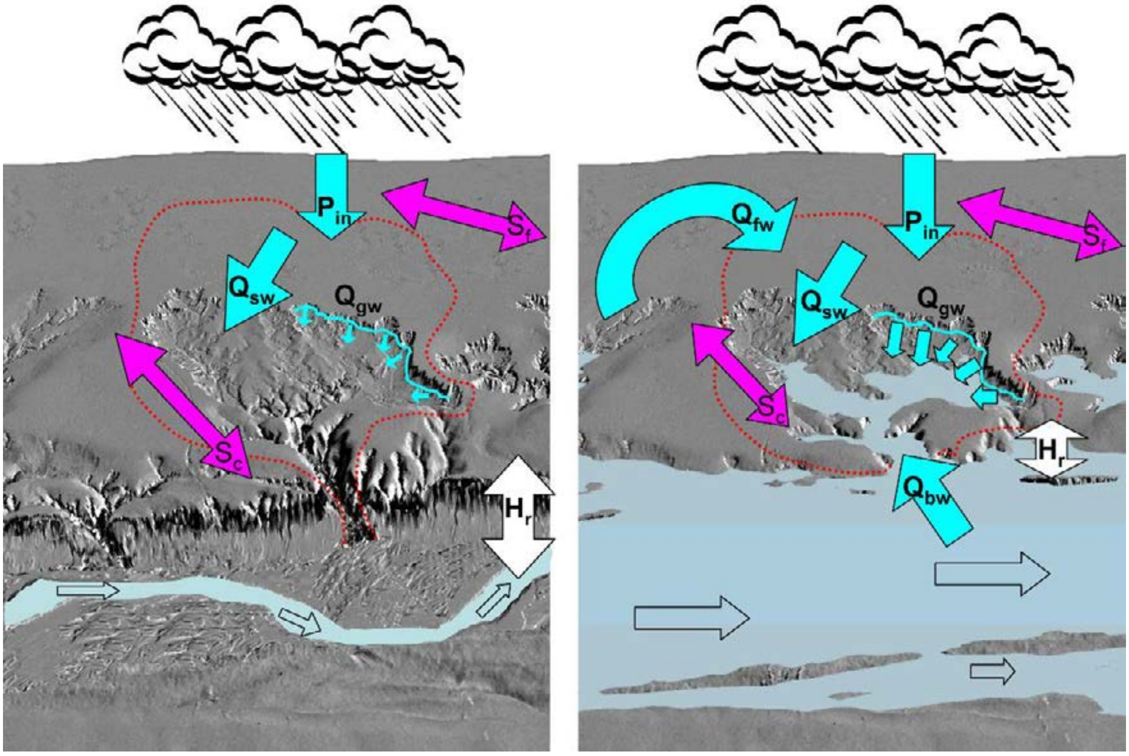
Alluvial gullies are typically concentrated at or near (< 3 km) the banks of main floodplain channels, where there is a break in slope on steep banks (Figure 2; AGSO 1995; Brooks et al. 2009). The elevational relief or vertical height between the river bed and high floodplain or terrace provides the potential energy for erosion. This height can be enhanced by river incision or entrenchment into the surrounding floodplain over geologic time (Brooks et al. 2009; Shellberg et al. 2013a). The heights of gully head scarps are often correlated to this local relief and degree of river entrenchment (Brooks et al. 2009).

The kinetic energy for alluvial gully erosion can come from multiple water sources such as direct rainfall, overland runoff, groundwater, river backwater, or overbank floodwater into subtle gully catchments that are difficult to delineate on the ground (Figure 6; Brooks et al. 2009; Shellberg et al. 2013a). This is in contrast to hillslope or colluvial gullies that have standard rainfall-runoff responses and easily definable catchment areas. Since alluvial gullies are often situated on floodplains and terraces near rivers and water bodies, river backwater or overbank flood water can contribute significantly to gully erosion (Shellberg et al. 2013a). The importance of these erosional drivers depends on the connectivity of the river with its floodplain or terrace, which is spatially controlled by the degree of river incision or entrenchment (Brooks et al. 2009; Shellberg et al. 2013a). It is also temporally controlled by the frequency and magnitude of flood runoff from the river catchment (Shellberg et al. 2013a), as influenced by climate and human development. However since a majority of alluvial gullies erode into terraces or elevated floodplains, complete overbank flooding on these surfaces is infrequent and river backwater is more common. Thus for a majority of the time, erosion from intense tropical rainfall on exposed soils and overland runoff from surrounding subtle catchment areas dominates alluvial gully erosion and scarp retreat (Shellberg et al. 2013a).

The erodibility of terrace and floodplain soils plays a major role in the initiation, propagation, and distribution of alluvial gullies. Older, elevated, near-river, soils (terraces and levees) in the Australian tropical savannas are often highly weathered silty loams or silty clays, compared to sandy soils in-river and clay soils in distant floodplains (Galloway et al. 1970). Depending on the catchment parent geology, these floodplain soils can have elevated levels of exchangeable sodium percentage (ESP) and magnesium percentage (EMP) attached to clay particles, relative to preferred levels of calcium and potassium. These sodic soils (Sodosols) are often textural-contrast duplex soils, typically with a thin A-horizon of topsoil that overlies massive sodic sub-soil clays that are highly dispersive and erodible (Isbell et al. 1968; Galloway et al. 1970; Biggs and Philip 1995a; 1995b; AGSO 1995; Shellberg 2013a). Once these topsoils are disturbed, degraded and cut into by natural and human factors, scalding and alluvial gully erosion can result.

The distribution of sodic soils on alluvial floodplains in northern Queensland has been mapped during regional soil resource inventories by government departments (Isbell et al. 1968; Galloway et al. 1970; BRS 1991; Biggs and Philip 1995a; 1995b). Many of these sodic soil locations coincide with recent mapped distributions of alluvial gully erosion (AGSO 1995; Brooks et al. 2006; 2007; 2008; 2009; 2012; 2013; Knight et al. 2007). Together these mapping efforts can be used to identify areas at high risk for alluvial gully erosion (AGSO 1995), for which tailored land management strategies could be developed to reduce gully initiation and acceleration (Section 2.8).

Vegetation on banks and elevated floodplains play the key mitigating role in resisting alluvial gully erosion into dispersive or sodic soils. Perennial grasses perform best at protecting and binding *surface* soils to prevent erosion initiation. Native perennial grasses typically have deep roots that bind topsoils and improve infiltration. However, some exotic perennial grasses with stoloniferous nodes can provide an even cover distribution, resulting in reduced water velocity, increased water detention and infiltration, and reduced water runoff volumes (Scanlan et al. 1996). Tree, shrub and exotic weed species can are also important in providing cover and erosion resistance, but are less effective at protecting and binding surface soils compared to perennial grasses. Both natural factors such as drought and fire, and anthropogenic factors such as grazing, fire regime changes, weed invasion, fencing, roads, tree clearing, and agriculture can influence vegetative cover and erosion resistance (Shellberg 2011). Runoff volumes from alluvial gully catchments can be increased by low levels of ground cover (Shellberg et al. 2013a), enhancing erosion susceptibility or rates. Animal tracks (pads) and roads that concentrate water can also overwhelm the effectiveness of grass cover in resisting soil and gully erosion (Shellberg 2011; this report).



a) b)

Figure 6 Conceptual model of erosional-drivers of alluvial gully erosion with approximate catchment area in red: a) low river water and high relative relief (H_r) when water sources are dominated by direct precipitation (P_{in}), surface water from overland flow off the floodplain (Q_{sw}), and emergent soil moisture (or groundwater) at breaks in slope (Q_{sm}); and b) high river water and low relative relief (H_r) when water sources additionally include river backwater (Q_{bw}) during common floods and overbank floodplain water (Q_{fw}) during larger magnitude floods. Potential energy factors include relative relief (H_r), the alluvial gully channel slope (S_c), and the often smaller floodplain slope (S_f) (Shellberg et al. 2013a).

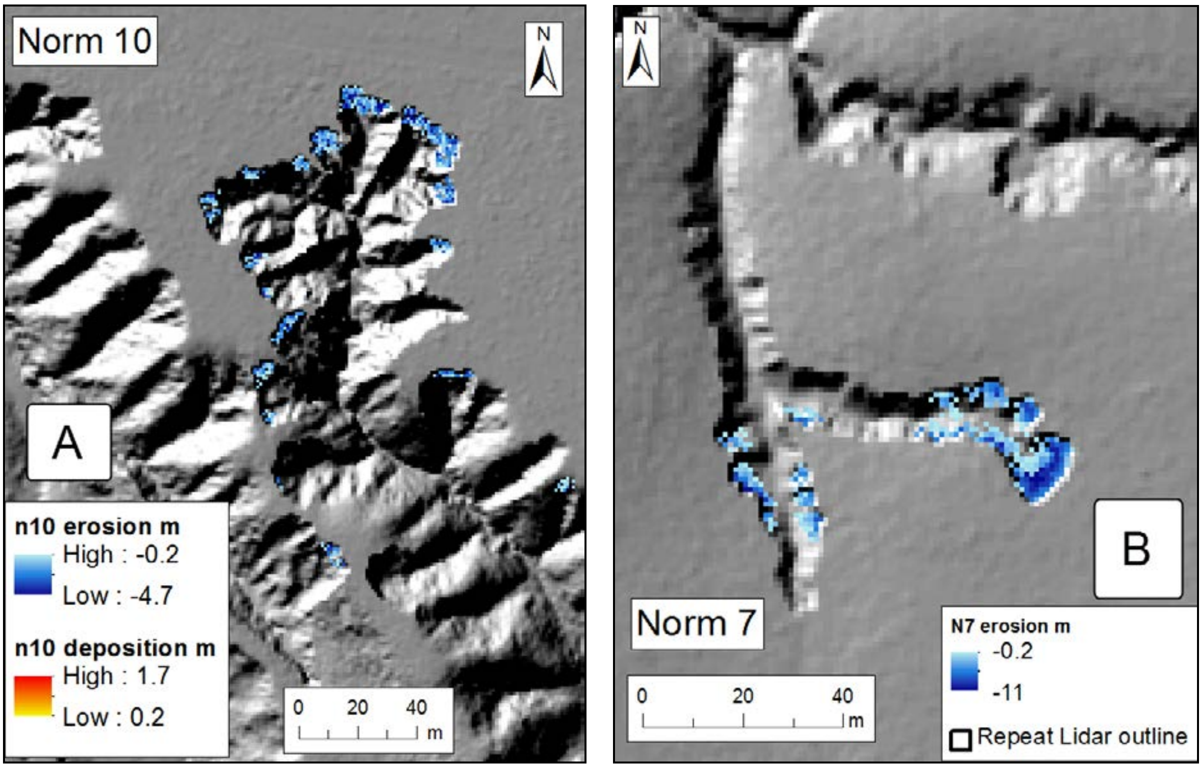
2.5 Rates of Gully Expansion

Rates of linear and aerial gully expansion can vary widely depending on the location and erosion process. Recent (2005-2010) GPS surveys at 18 sites in the Mitchell catchment measured average linear rates of scarp retreat between <0.1 and 0.8 m/yr, with a median rate of 0.23 m/yr (Shellberg 2011). However, maximum local rates at active lobes ranged between 2 and 15 m/yr, with rates up to 75m/yr associated with roads (Brooks et al. 2009; Shellberg 2011). In the Normanby catchment, recent maximum rates of gully expansion were up to 20m/yr, but more typical maximum extension rates were 1-2m/yr (Figure 7). However, average values along long scarp fronts are less than 0.5 m/yr (Brooks et al. 2013).

Using historical aerial photos between the 1940s and 2000s, similar average linear rates of scarp retreat have been documented in the Mitchell (median 0.37 m/yr; range <0.1 to 1.2; Shellberg et al. 2010; Shellberg 2011), Normanby (median 0.46 m/yr; range 0.1 to 0.7; Brooks et al. 2013) and Victoria NT (average 0.86 m/yr; range 0.3 to 1.6; McCloskey 2010) catchments. In the Mitchell catchment, historic gully areas have increased between 1.25 to

10 times their initial 1949 area (Figure 8). Extrapolation of gully area growth trends backward in time suggests that the current phase of extensive gullying was initiated between 1880 and 1950 in the Mitchell (Shellberg et al. 2010; Shellberg 2011). Spatial and temporal projections of gully area growth into the future, until channel profile equilibriums are reached, suggest that alluvial gullies will continue to be chronic erosion features on the landscape for several hundred to several thousand years, growing 10 to 50 times their initial 1949 size, unless mitigated by land management intervention (Shellberg 2011).

In the Normanby catchment where exposed alluvial gully erosion areas are generally smaller than the Mitchell and more difficult to measure via aerial photos, historic gully areas have increased up to 3 times their initial 1949 area (Figure 9). Extrapolation of gully area growth trends backward in time suggests that some gullies initiated between 1880 and 1930 during the current phase of gullying, while an older phase of gullying initiated before 1850 (Figure 9; Brooks et al. 2013).



A) B)

Figure 7 Examples of alluvial gully head extension from the Normanby catchment over a two year period (2009-2011) measured by repeat airborne LiDAR data at A) a mature amphitheatre-shaped gully on a river bank, and B) an incipient linear gully eroding into a floodplain (Brooks et al. 2013).

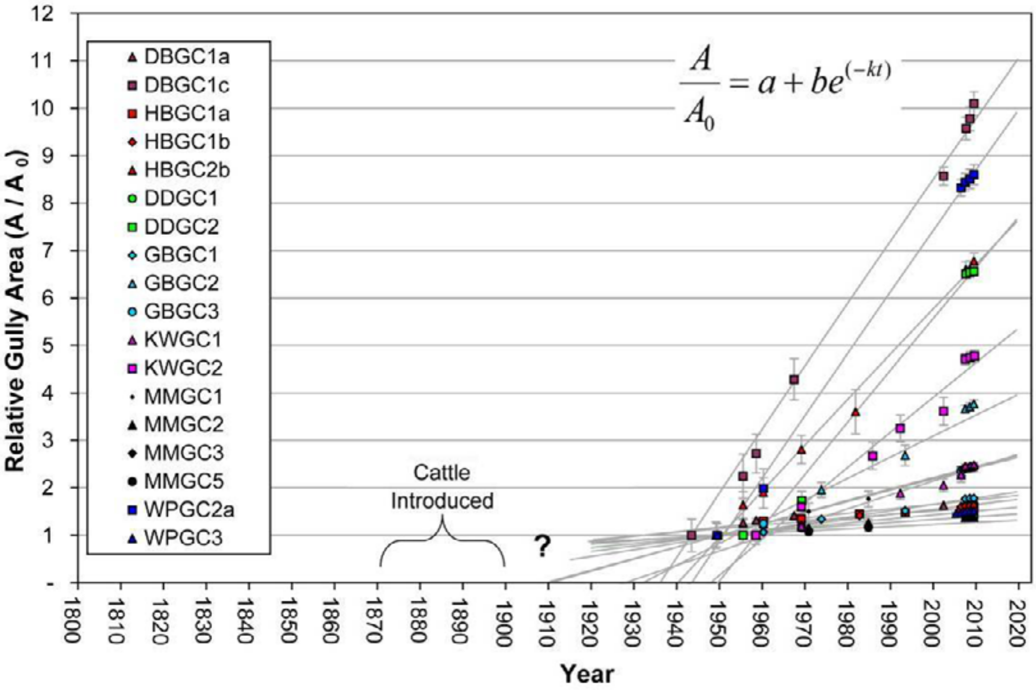


Figure 8 Mitchell Catchment: Relative changes in gully area (A/A_0) over time at 18 alluvial gully sites in the Mitchell catchment fitted with a negative exponential function (with near linear results) (Shellberg 2011).

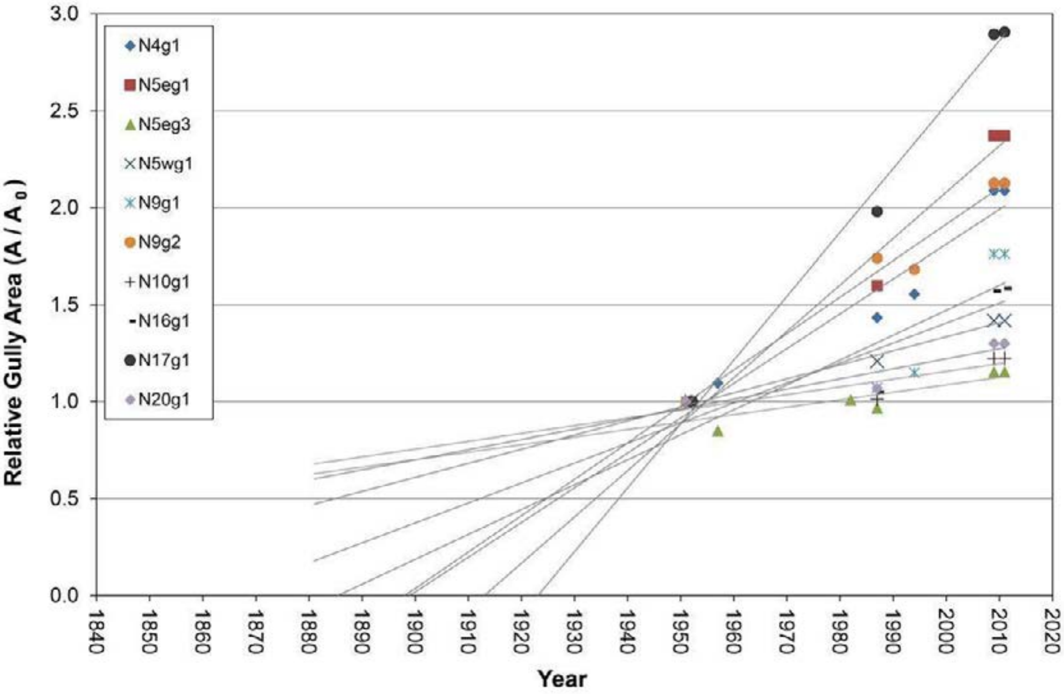


Figure 9 Normanby Catchment: Relative changes in gully area (A/A_0) over time at 10 alluvial gully sites in the Normanby catchment fitted with a linear function. Two phases of initiation are suggested by these data. A phase between 1880 and 1930, and a phase prior to 1850 that cannot be accurately assessed due to limitations of the data set (Brooks et al. 2013).

2.6 Initiation and Acceleration by Human Land Use

Detailed reviews of the journals of historical explorers in the Mitchell (QLD, Shellberg et al. 2010; Shellberg 2011) and Victoria (NT, McCloskey 2010) catchments indicate that severe gully erosion was not common nor widespread pre-European settlement, but that earlier forms of flood drainage channels (FDCs, McCloskey 2010), un-channelled floodplain hollows (Shellberg et al. 2010; Shellberg 2011), and old river paleo-channels did exist near the banks of floodplain rivers. Earlier phases of channel and gully network development into floodplain alluvium existed in the Normanby and Mitchell catchments (see below; Shellberg 2011; Shellberg et al. 2013a; Shellberg et al. 2013b; Brooks et al. 2013). However, these features were largely rounded and quasi-stable upon the arrival of Europeans (Shellberg 2011; Brooks et al. 2013). Precursing drainage forms were often the locations where the current phase of extensive gully erosion initiated and developed (Figure 10); however alluvial gullies have also initiated on steep river banks without associated drainage channels. The processes that created the *rounded* floodplain hollows and drainage channels over long time periods (pre-European) could have been fundamentally different (slower surface erosion via local diffusion of soil) than the rapid expansion of *headcutting* alluvial gullies observed during historic times (faster channel incision leading to sediment advection and export). However, more detailed investigations of gully erosion *processes and rates* pre-European settlement are needed to interpret the variety of past and present gully forms and rates seen today in the Normanby and Mitchell catchments and beyond.


a) b)

Figure 10 Examples of a) a small alluvial gully on a river bank eroding into b) an un-channelled floodplain hollow immediately upstream, that will eventually develop into a large alluvial gully similar to Figure 3b and Figure 4c.

In the Mitchell catchment, multiple lines of evidence indicate that the rapid historical rates (last 130 yrs) of widespread alluvial gully expansion were unprecedented in scale, despite earlier phases of less developed floodplain erosion during the Holocene. This assertion is supported by historical rates of expansion from aerial photos (Figure 8), young optically stimulated luminescence (OSL) dates of gully inset-floodplain deposits, Light Detection and Ranging (LiDAR) terrain analysis, historic explorer accounts of earlier drainage channel types, and archival records of cattle numbers and land management (Shellberg et al. 2010; Shellberg 2011). Since the late 1880s, the introduction of hard-hoofed cattle and steady increases in herd sizes have fundamentally changed the way land is managed in northern

Australia (Condon 1986; Winter 1990; Pusey 2011; Shellberg et al. 2010; Shellberg 2011). From multiple lines of evidence, it is concluded that intense cattle grazing concentrated in the riparian zones during the dry season increased the potential for gully erosion initiation in the wet season along steep banks, floodplain hollows and precursor channels (Condon 1986; Shellberg et al. 2010; Shellberg 2011). This is a result of reduced native grass cover, increased physical disturbance of soils, and the concentration of runoff down cattle tracks over steep banks used to access water (Condon 1986; AGSO 1995; Brooks et al. 2009; MCloskey 2010; Shellberg et al. 2010; Shellberg 2011), which were possibly coupled with episodic drought, the invasion of exotic weed and grass species, fire regime modifications (Stafford-Smith et al. 2007; Neldner et al. 1997; Fensham and Skull 1999; Sharp and Whittaker 2003; Crowley and Garnett 1998, 2000; Russell-Smith et al. 2003), and more recently road and fence construction. Or in other words, the natural factors mentioned above primed the floodplain landscape for erosion over long geologic time periods, but land-use change pushed the landscape across a threshold towards instability and triggered accelerated, widespread, and massive alluvial gully erosion (e.g., Figure 1).

In the Normanby catchment, several erosion cycles of drainage network development eroding into older floodplains have been documented from 1) the post-European settlement period and 2) during the Holocene (<10,000 yrs) (Figure 7; Figure 11; Brooks et al. 2013). The earlier erosion phases of drainage networks into the floodplain created the template upon which the current active phase of alluvial gullying is overwritten. The combined area extent of the prior phases of gullying is around an order-of-magnitude greater than the currently active phase, but this area was eroded and created over longer time periods during the Holocene. However, the most recent post-European phase cut channels deeper than the earlier phases and had gully erosion and deposition rates greater than 10 times that during the Holocene (Figure 11). For example, the late-Holocene fill unit (235 to 900 years) in Figure 11 had deposition rates of 0.5 mm/yr, while the post-European fill unit (14-17 years) had minimum rates of 14 mm/yr. Shellberg (2011) found similar changes to gully deposition rates in the Mitchell catchment. This order-of-magnitude (10x) increase in erosion and deposition also does not account for the subsequent increase in sediment liberated by the deep gully incision that exposed this gully profile, which would have elevated sediment yields even more. Aerial photo analysis in the Normanby catchment also suggests that many recent gullies have been initiated in the post-European period (Figure 9).

These data in combination suggests that the recent phase of gully erosion is more extreme than the previous phase(s). The earlier phases highlight a sensitive landscape prone to alluvial gully erosion (e.g., dispersive soils, river incision). The most recent rejuvenation phase can be tied to the introduction of cattle, cutting of cattle tracks (pads) that concentrate water flow along riparian zones, reduction of grass cover, and an increase in water runoff from floodplain slopes into gullies accelerating erosion (this report; see below).

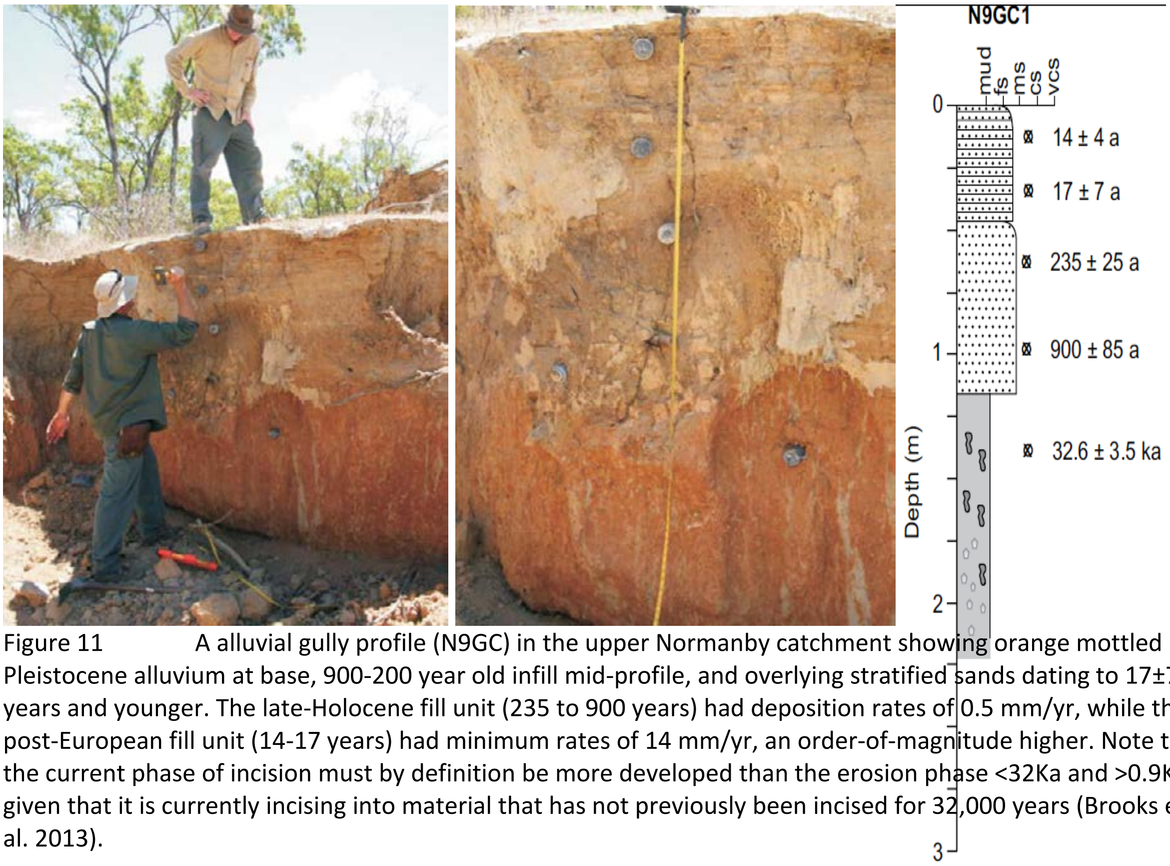


Figure 11 A alluvial gully profile (N9GC) in the upper Normanby catchment showing orange mottled Pleistocene alluvium at base, 900-200 year old infill mid-profile, and overlying stratified sands dating to 17±7 years and younger. The late-Holocene fill unit (235 to 900 years) had deposition rates of 0.5 mm/yr, while the post-European fill unit (14-17 years) had minimum rates of 14 mm/yr, an order-of-magnitude higher. Note that the current phase of incision must by definition be more developed than the erosion phase <32Ka and >0.9Ka, given that it is currently incising into material that has not previously been incised for 32,000 years (Brooks et al. 2013).

Across northern Australia, the current and historic grazing management paradigm (Winter 1990) consists of grazing down grass cover to minimal levels in the late-dry season along river frontage, with accompanying dense cattle tracks (pads) cut into steep banks to access river water and episodic fire burning of remnant vegetation in the late-dry and early-wet seasons. This management paradigm results in exposed and disturbed erodible soils at the beginning of the tropical monsoon rains. Initiation and acceleration of alluvial gully erosion can be the result (Condon 1986; Winter 1990; AGSO 1995; Shellberg 2011). While dense cover of native deep-rooted perennial grass is key to binding erodible soils together, large networks of cattle tracks over steep banks to access water daily can overwhelm good vegetative cover by concentrating overland flow and initiating gullying (Figure 12a; Section 6.3; Condon 1986; AGSO 1995; Shellberg 2011). Once the critical A-horizon soil is breached – exposing the dispersive, sodic, clay sub-soils – there is little stopping the rapid development and propagation of alluvial gullies. A similar effect is caused by poorly located, constructed, and maintained roads (Figure 12b; Section 6.5.9; 7.14), which are rapidly becoming more common sediment sources as development advances across northern Australia.


a) b)

Figure 12 Examples of a) a cattle track (pad) cut down a steep river bank that is rapidly being transformed into an alluvial gully, and b) an alluvial gully initiated by a poorly designed road crossing a river.


a) b)

Figure 13 Examples of cattle tracks (pads) collecting and concentrating water runoff into gully headcuts in the Normanby catchment.

2.7 Sediment Production from Alluvial Gullies

Alluvial gullies are highly concentrated, well connected, and major sources of sediment to river systems. Suspended sediment concentrations (SSCs) transported out of alluvial gullies in the Mitchell and Normanby catchments typically are > 10,000 mg/L and can exceed 100,000 mg/L from the largest gullies during peak runoff (Shellberg 2011; Shellberg et al. 2013b; Shellberg unpublished data). This is in contrast to SSCs measured in nearby river samples that are typically less than 1,500 mg/L, but with larger water volumes (Rustomji et al. 2010; Brooks et al. 2013; Howley et al. 2013). The combination of highly erodible soils, rapid scarp retreat, intense tropical rainfall and runoff, and high sediment concentrations can lead to high local sediment yields (up to 350 t/ha/yr) (Brooks et al. 2008; Rustomji et al. 2010; Shellberg et al. 2013b), which are high by both Australian and world standards for soil and gully erosion (Shellberg et al. 2013b).

In the Mitchell catchment, distributed measurements of scarp retreat rates, scarp heights, soil bulk densities, and particle size distributions, along with ASTER satellite mapped distributions of alluvial gullies, were used to estimate total sediment production from alluvial gullies at the catchment scale. Sediment production estimates from alluvial gullies across the Mitchell megafan suggest that ~ 6.3 Mt/yr were eroded historically (1949-2006), compared to ~3.9 Mt/yr recently (2006-2010) (Brooks et al. 2008; Rustomji et al. 2010;

Shellberg 2011), with slightly faster rates possible during the initial phases of disturbance (Shellberg et al. 2010; Shellberg 2011). These erosion rates are higher than total sediment transport rates estimated at downstream river gauges (<2 Mt/yr; Rustomji et al. 2010; Shellberg 2011), indicating that much of this eroded sediment is deposited locally or along long lengths of river channel. This is supported by observations of lagoon and channel infilling and measured sedimentation rates exceeding 2 kg/m^2/yr on river inset-floodplains and benches (Shellberg 2011).

Across northern Australia, sediment tracing research of fine suspended sediment (less than 10um) suggests that sub-surface erosion sources (i.e., channel bank erosion, gully erosion, deep rill erosion, and mass wasting) dominate the overall sediment budgets (Wasson et al. 2010; Caitcheon et al. 2012; Brooks et al. 2013; Wilkinson et al. 2013; Olley et al. 2013). For example, in the lower Normanby catchment it was estimated that 87% of particles < 10um originated from sub-surface sediment sources (Brooks et al. 2013; Olley et al. 2013). In the Mitchell catchment it was estimated that sub-surface sources represented 97% of sediment contributions (Caitcheon et al. 2012).

Independent sediment budget estimates for the Normanby catchment indicate that sub-surface bank erosion from small alluvial channels and alluvial/colluvial gullies together dominate the overall sediment budget (91% of sediment inputs), in contrast to sediment loads from hillslope surfaces that are several orders of magnitude lower (Brooks et al. 2013). In the Mitchell at the catchment scale, alluvial gully sediment sources likely dominate the fine sediment budget (>50% of the sediment inputs; Rustomji et al. 2010). However, bank erosion cannot be discounted (Brooks et al. 2008; Rustomji et al. 2010) and other significant sources of sediment from small channels, mining, agriculture, and roads remain poorly quantified (Rustomji et al. 2010).

In the Normanby catchment, alluvial and colluvial gullies were mapped using a combination of Spot & Quickbird imagery across the whole catchment and repeat LiDAR data (2009; 2011) distributed across 3% of the catchment (Brooks et al. 2013). The LiDAR data were used to correct the Spot & Quickbird imagery to better extrapolate the extent of gullies across the catchment (Figure 14; Figure 15). Area erosion rates measured from historical aerial photographs were then used along with LiDAR and corrected gully distribution data to calculate erosion volumes across the catchment. The erosion mass for fine suspended sediment (silt, clay, <63um) was estimated using bulk density and particle size distribution. From these data, it was estimated that 736,400 t/yr of fine sediment (<63um) were eroding from alluvial gullies during the historic aerial photo period, compared to 411,800 t/yr for colluvial gullies (Brooks et al. 2013). From LiDAR data, it was apparent that many of the colluvial hillslope gullies were functionally linked to the alluvial gullies, via downslope initiation as alluvial gullies extended across floodplains into hillslope colluvium.

In the Normanby Catchment, it was estimated that alluvial and colluvial gullies together produce 37% of the fine sediment inputs (1,148,200 t/yr; Figure 16; Brooks et al. 2013). The major source of fine sediment was estimated to originate from bank erosion along small alluvial secondary channels (54%; 1,672,000 t/yr) primarily located just downstream of gully networks. Bank erosion along larger river channels was estimated to be 8% (249,900 t/yr) of the inputs, while fine sediment from hillslopes represented just 1% (15,900 t/yr) of total sediment input. Hillslope erosion measurements were 1 to 4 orders of magnitude less than previous modelled estimates (Brooks et al. 2013). Sediment sinks via deposition within the river system were estimated as > 424,000 t/yr for river benches and 1,270,000 t/yr for floodplains. This indicated that a significant portion of the sediment derived from gullies and bank erosion could be accommodated within the river system and not exported to sea. All of these data have large error margins of uncertainty (likely ± 50% or more for each budget component) and the exact relative contributions could be influenced by unmeasured components and residuals (e.g., surface hillslope erosion internal to gully networks not measured by LiDAR; deposition in lagoons and wetlands; coastal plain erosion; etc.) (Kondolf and Matthews 1991). However, they do highlight the current understanding of the relative importance and magnitude of different sediment sources and sinks in the Normanby and are useful for targeting remediation measures at the sub-catchment scale.

These data in combination suggest that all sub-surface sediment sources (i.e., channel bank erosion, gully erosion, deep rill erosion, and mass wasting) should be targeted for further investigation and management actions to reduce sediment erosion and yields to downstream receiving areas such as mainstem rivers, wetlands, estuaries, coasts, and off-shore reef environments.

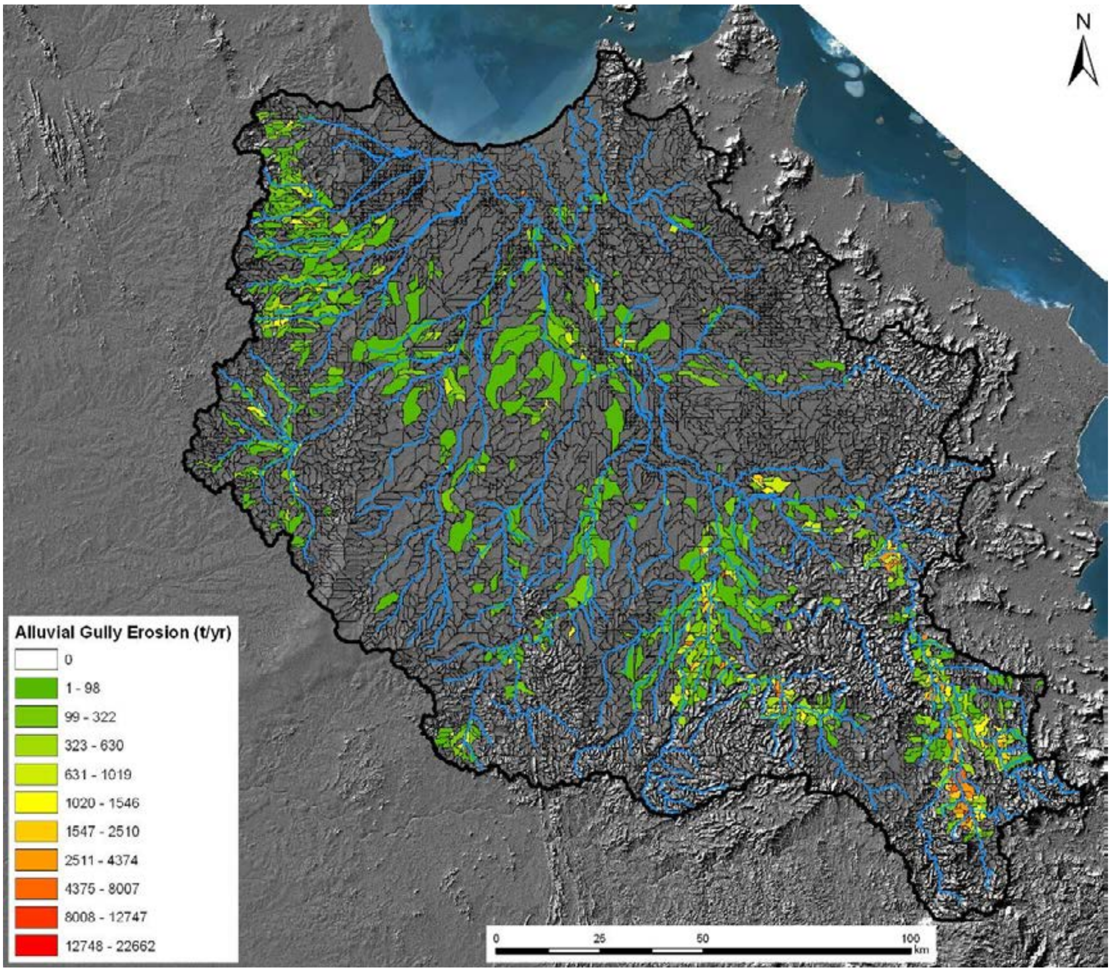


Figure 14 Alluvial gully erosion distribution and erosion rates [Log 10 (t/yr)] within the Normanby catchment estimated from Spot & Quickbird imagery, LiDAR data and historical aerial photographs (Brooks et al. 2013).

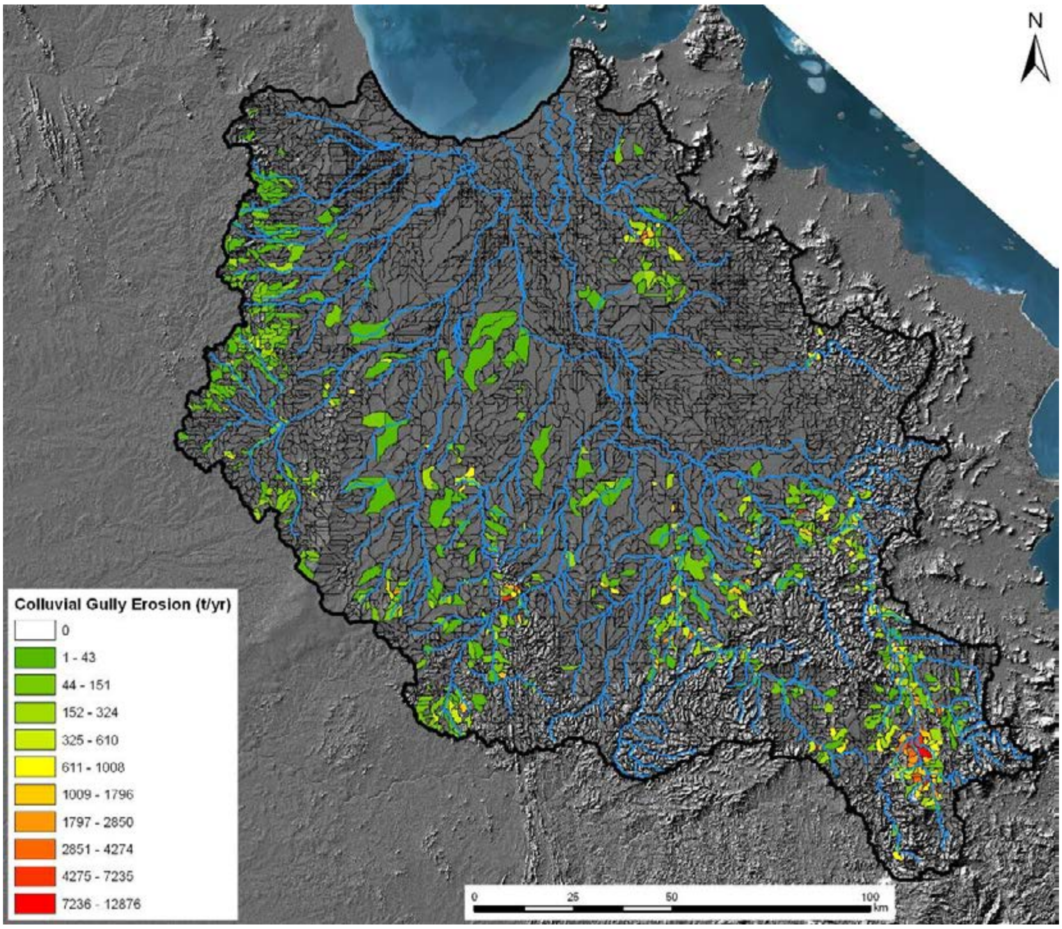


Figure 15 Colluvial gully distribution and erosion rates (t/yr) within the Normanby catchment estimated from Spot & Quickbird imagery, LiDAR data and historical aerial photographs (Brooks et al. 2013).

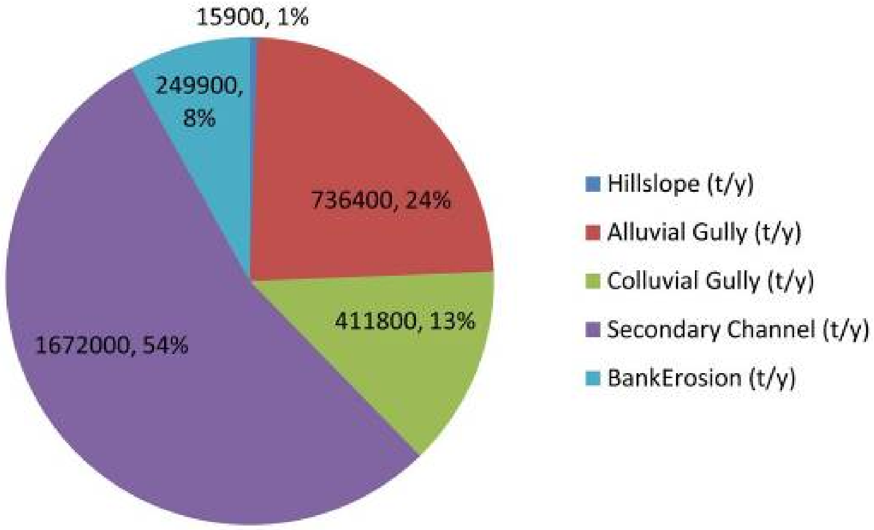


Figure 16 Relative contributions of suspended sediment to the Normanby stream network – based on the model output. Note secondary channel erosion primarily represents bank erosion within small alluvial tributaries (Brooks et al. 2013).

2.8 High Risk Areas of Alluvial Gully Erosion along River Frontage in the Normanby

Existing data on soil type (i.e., dispersive or sodic soils) and gully erosion extent and rates have been used in combination to delineate areas of high risk to alluvial gully erosion along river frontage. These data and maps can be used to tailor land management strategies to reduce gully initiation and acceleration.

In the Mitchell catchment, mapped areas of alluvial gully erosion (Brooks et al. 2006; 2007; 2008; 2009; Knight et al. 2007) are concentrated along the river frontage at or near (< 3 km) the banks of main river and creek channels, where steep banks and local relative relief provide the potential for erosion. These gully erosion areas also coincide with mapped zones of dispersive sodic soils (elevated exchangeable sodium) that have a predisposition to erosion if disturbed (Isbell et al. 1968; Galloway et al. 1970; BRS 1991; Biggs and Philip 1995a; 1995b).

In the Normanby catchment, mapped areas of alluvial gullies from Google Earth images (Brooks et al. 2013) were overlayed with soil surveys (Biggs and Philip 1995a; 1995b) and erosion hazard mapping (AGSO 1995) to generate a catchment wide map highlighting the areas most prone to alluvial gully erosion (Figure 17; Figure 18). Notable high risk areas of gully erosion are located on river terraces next to incised river channels along the Laura River between Lakeland and Laura, along the Granite Normanby River, near the East/West Normanby River confluence, and the lower mainstem Laura and Normanby Rivers (Figure 14; Figure 18). These high risk areas coincide with mapped dispersive sodic soils (elevated exchangeable sodium at depth) along elevated alluvial terraces, river frontages, and steep river banks (AGSO 1995; Biggs and Philip 1995b; this report). Gully erosion into these soils is caused by a combination of factors including 1) natural processes [river incision, soils, rainfall, runoff], 2) disturbance of river banks and floodplains by cattle, and 3) incorrect construction of roads and fences (reviewed in AGSO 1995; Shellberg et al. 2010; Shellberg 2011; this report).

Biggs (in AGSO 1995) summarised the key land management recommendations for these soils at high risk to alluvial gully erosion: *“Areas containing erodible soils must be managed on a landscape basis, with both onsite and off-site consequences taken into account. Dam and road construction, as well as stocking rates and patterns need to acknowledge the inherent erodibility of certain soils”*.

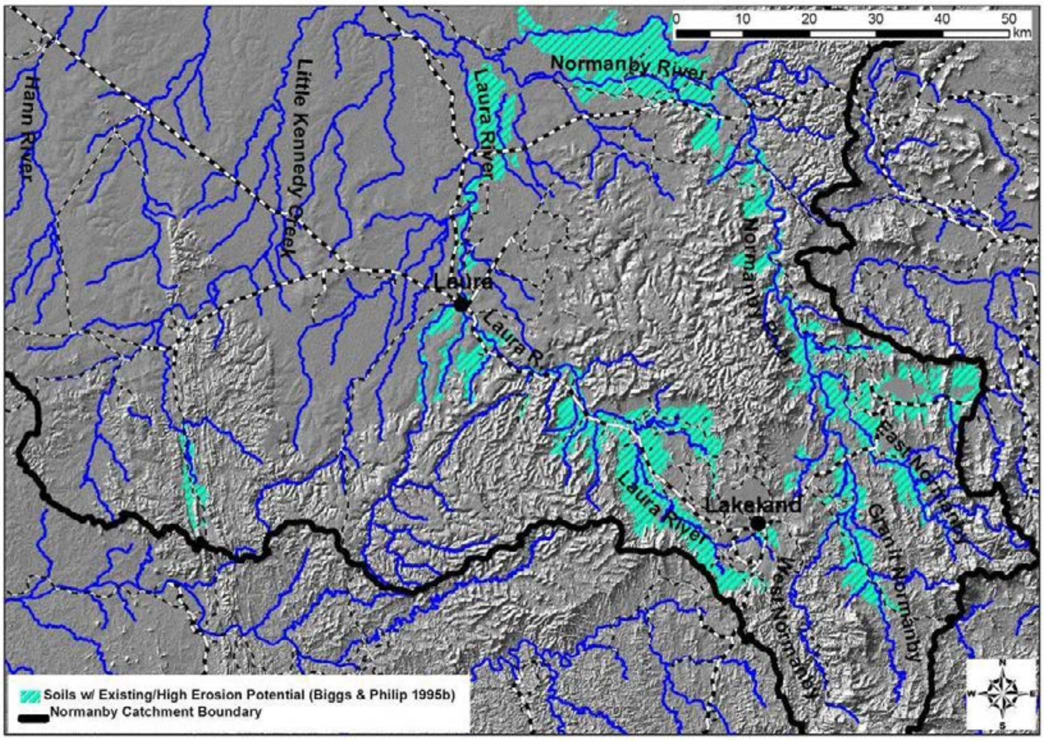


Figure 17 High risk areas of soil erosion in the upper Laura-Normanby catchment, based on soil surveys (Biggs and Philip 1995a; 1995b), erosion hazard mapping (AGSO 1995), and field observations.

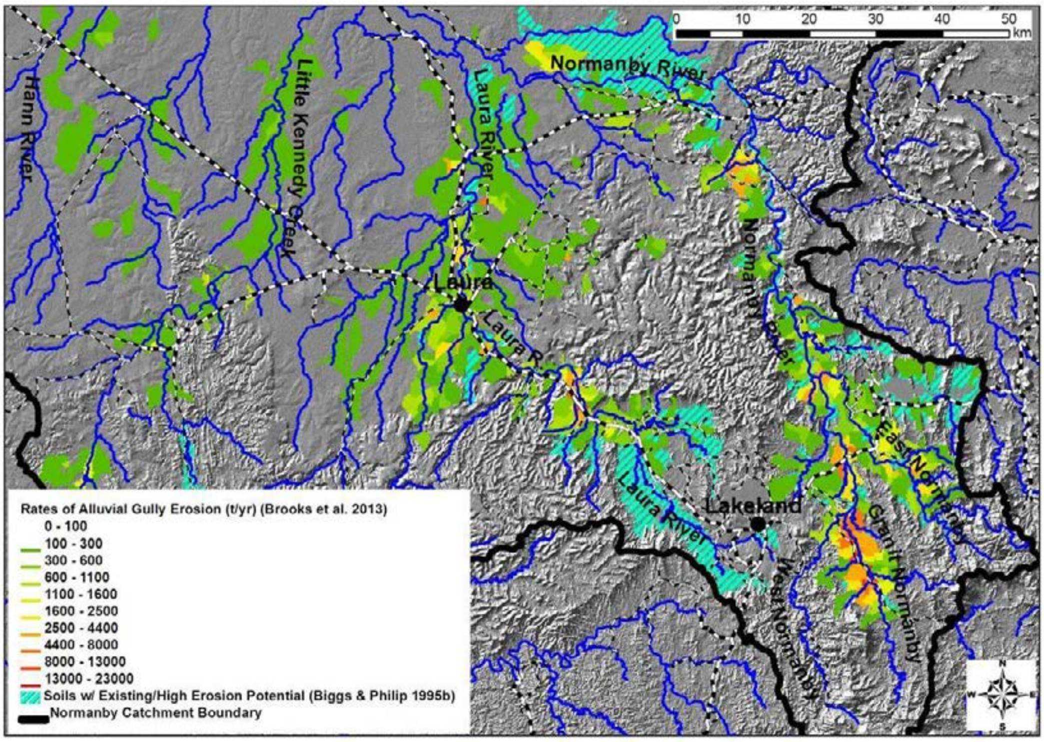


Figure 18 High risk areas of alluvial gully erosion in the upper Laura-Normanby catchment, based on Google Earth gully distribution data, measured and modelled (extrapolated) gully erosion rates (Brooks et al. 2013). Soils with existing high risks of erosion from soil surveys and hazard mapping (Biggs and Philip 1995a; 1995b; AGSO 1995) are also included, and underlay most of alluvial gully rate mapping (Figure 17).

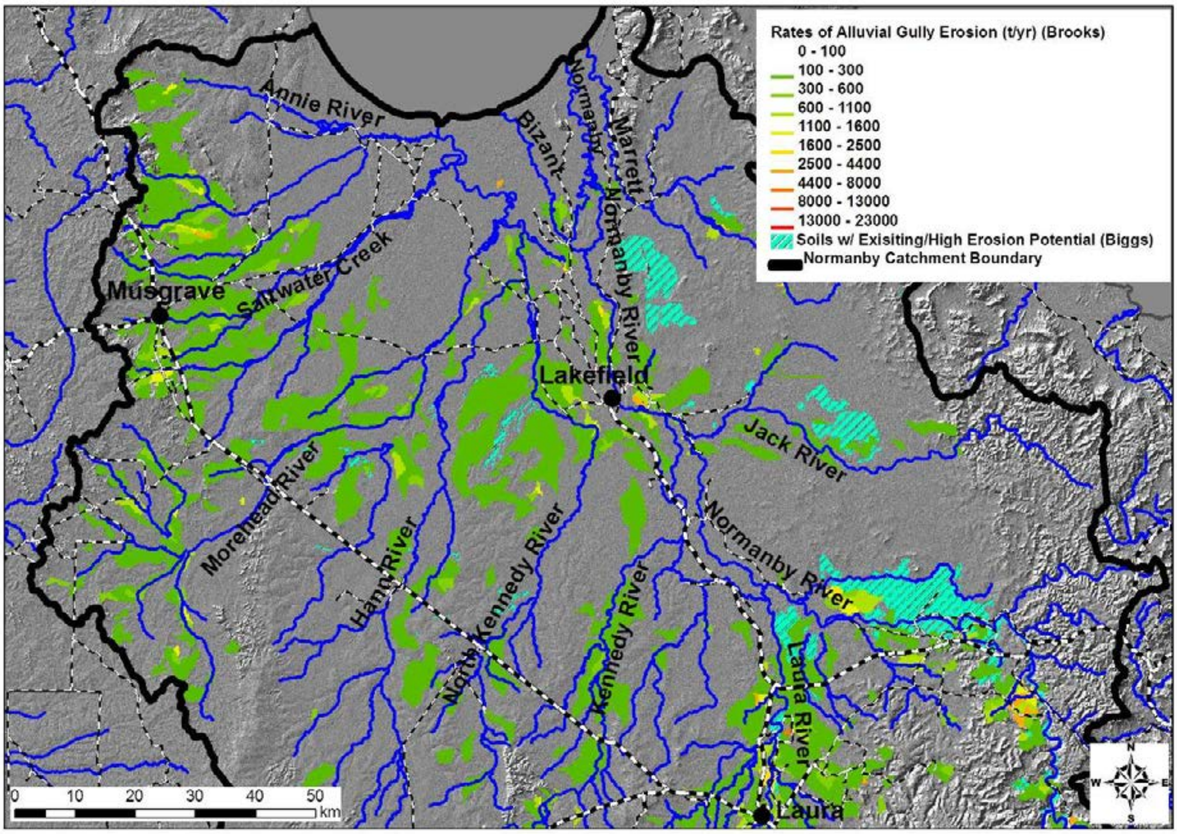


Figure 19 High risk areas of alluvial gully erosion in the lower Normanby catchment, based on Google Earth gully distribution data, measured and modelled (extrapolated) gully erosion rates (Brooks et al. 2013). Soils with existing high risks of erosion from soil surveys and hazard mapping (Biggs and Philip 1995a; 1995b; AGSO 1995) are also included.

3 Why the Focus on Alluvial Gullies in the Normanby Catchment?

The Australian Government Reef Rescue program is currently investing in cooperative cost-share management actions with local landowners to reduce fine sediment and associated nutrient input to the Great Barrier Reef Lagoon to minimise human land use impacts to the health of the reef (QDPC 2009; Waterhouse 2010). Other industry, State, Federal, and Indigenous run programs are also interested in reducing sediment erosion and delivery to waterbodies in the Normanby catchment to 1) maintain the productivity of grazing and agricultural properties via soil health, 2) increase stores of soil carbon, 3) reduce the sedimentation of freshwater ecosystems such as river, wetlands, lagoons, and estuaries, and 4) maintain and respect the social and cultural values imbedded in freshwater and marine resources (Cotter 1995; AGSO 1995; Mitchell and Hardwick 1995; Bassani et al. 2006; Cook et al. 2011; Carter et al. 2012; Howley et al. 2013).

The widespread distribution and large area of alluvial and colluvial gullies across the Normanby catchment (Figure 14; Figure 15; Figure 18; Table 1) indicate that gullying is a fairly common phenomenon that catchment land managers encounter. Interviews with land managers have identified concerns regarding the impact on and loss of human infrastructure (e.g., roads, fences, buildings, dams, and other water points) from gully erosion (e.g., Figure 20; Figure 21), as well as loss of productive riparian land for grazing or potential agricultural development (e.g., Figure 22). Downstream land and resource managers are also concerned about the influence of gully erosion on the integrity of freshwater wetlands and lagoons (Howley et al. 2013). Scientific data suggest that there is a connection between the acceleration of alluvial gully erosion and cattle grazing practices over the last 130 years (Shellberg et al. 2010; Shellberg 2011; Brooks et al. 2013; Figure 8; Figure 9; Figure 11). Alluvial gully erosion has been accelerated by the introduction of cattle, cutting of cattle tracks (pads) that concentrate water flow, reduction of grass cover, and an increase in water runoff from floodplain slopes into gullies. Improperly placed, constructed and maintained fence lines and roads have also accelerated gully erosion (Shellberg 2011; Brooks et al. 2013). In summary, the direct and indirect connections between land use and gully erosion highlight that land management and rehabilitation actions could be used to minimise further gully initiation and reduce existing erosion rates. These actions can also be targeted at gully erosion threats to human infrastructure (e.g., roads, fences, yards, buildings, dams, and other water points).

Figure 20 A fence line (left) and road (right) threatened by alluvial gully erosion in the Normanby catchment.

a) b)

Figure 21 A stock water dam from the a) air and b) ground in the Normanby catchment threatened by gully erosion.

Figure 22 Cleared pasture land threatened by alluvial gully erosion in the Normanby catchment.

While bank erosion issues and concerns are less commonly encountered by land managers in the Normanby catchment, sediment budget analysis indicates that bank erosion is a major source of fine sediment, especially in small alluvial channels (Brooks et al. 2013). The potential land use impacts on main channel bank erosion are less clear due to relatively intact riparian forests along main river channels in the Normanby. However, it is likely that there are land use connections with the erosion of small alluvial channels, specifically through:

1. The direct disturbance of small channel banks by cattle hooves and over-grazing perennial grass vegetation could accelerate local bank erosion.
2. Increased water runoff associated with altered catchment-wide ground cover from over-grazing, fire regime changes, weeds, and extensive upstream gullying could accelerate bank erosion.
3. Changes in coarse sand sediment supply (e.g., from alluvial gullies) could increase bank erosion through channel infilling and lateral adjustments; or alternatively cut and fill cycles from changes in sediment supply could destabilise channel banks as part of a "complex response" to land use and/or natural disturbance.

The analysis of bank erosion processes and stabilization techniques in the Normanby catchment is currently part of a separate research project funded by Queensland Smart Futures Fund.

Reducing gully and bank erosion at a site-by-site basis to address cumulative impacts at the catchment scale in the Normanby remains problematic from physical, biological, chemical, economic and social perspectives, which will be discussed below. To reduce sediment loads at the catchment scale, it will be more pragmatic to address large concentrated areas of gully erosion in high risk areas (Figure 18) by changing existing land use paradigms towards those that promote soil conservation (AGSO 1995; Shellberg 2011; Brooks et al. 2013; this report).

4 The Need for Scientific Experimentation in Alluvial Gully Rehabilitation

The landscape in northern Australia has been degraded post-European settlement by unsustainable grazing and management practices (Condon 1986; 1988; Neldner et al. 1997; Fensham and Skull 1999; Crowley and Garnett 1998, 2000; Russell-Smith et al. 2003; Sharp and Whittaker 2003; Stafford-Smith et al. 2007; Shellberg et al. 2010; Shellberg 2011). This highlights the need for alternative and adaptive grazing management paradigms (e.g., Winter 1990) to be developed to slow or halt degradation such as accelerated alluvial gully erosion, and to improve the integrity of savanna grasslands and woodlands. However, before widespread soil conservation practices are implemented to reduce alluvial gully erosion initiation and acceleration, experimental trial rehabilitation programs and actions are needed to determine the most cost-effective, practical, non-degrading and sustainable land management and bioengineering activities to cumulatively reduce erosion at the catchment scale.

Despite many qualitative observations of the apparent successes and failures at reducing alluvial gully scarp migration and erosion in Northern Australia, to date there are few rigorous field data that quantify the effects of alluvial gully stabilization measures in isolation or in combination. Many earlier soil conservation programs in northern Australia (e.g., Ord River District) failed to fully address the critical erosion issues (i.e., gullies, Wasson et al. 2002). They were only marginally successful in stabilizing gully floors and head scarps using vegetation where conducted (Tongway and Ludwig 2002; Payne et al. 2004), despite being successful in revegetating denuded interfluves and shallow hillslopes after ripping, planting and removal of cattle (Hudson 1987; Sullivan and Kraatz 2001; Tongway and Ludwig 2002; Payne et al. 2004).

In northern Queensland, interest in alluvial gully rehabilitation is growing among numerous non-indigenous and indigenous land managers, hoping to slow or halt widespread land degradation along roads, fences, lagoons and river frontages. However, initial alluvial gully stabilization attempts have been ad hoc with mixed results (Shellberg 2011). They have focused heavily on engineering techniques that are hastily designed and often focus on symptoms (i.e., raw headcuts) rather than causes of erosion (i.e., excess water runoff, base level control). These techniques typically are neither sustainable nor process-based but can be practical in certain situations. Actions typically have not been based on lessons learned from gully reduction and stabilization techniques elsewhere in northern Australia, south-eastern Australia, or world-wide (see literature review below). Nor were these lessons adapted to the extremely unique situation of alluvial gully erosion (e.g., Brooks et al. 2009). The current understanding of the driving (geomorphic history, relief, climate, floodplain hydrology) and resisting (soil chemistry, vegetation cover) factors for alluvial gully erosion (Brooks et al 2009; McCloskey 2010; Shellberg et al. 2013a) and the human land-use contributions to this erosion (Condon 1986; 1988; Shellberg et al. 2010; Shellberg 2011) should be taken into account when planning and implementing future rehabilitation measures.

There is therefore a strong need for scientific quantification of alluvial gully rehabilitation measures and the associated geomorphic processes that are influenced by human intervention. Trial rehabilitation programs and demonstration projects are needed over the decadal time scale across multiple catchments with alluvial gullies (e.g., Normanby, Mitchell, Burdekin, Fitzroy, Gilbert, Leichhardt). The goal is to determine the most practical, cost-effective, non-degrading and sustainable land management and bioengineering activities to cumulatively reduce erosion at the catchment scale. Study designs should follow a before-after, treatment-control (BACI) approach (Underwood 1994a; 1994b; Smith 2002). An adaptive management component needs to be incorporated into experimental rehabilitation field trials in order to quantitatively learn from successes and mistakes in the trials, guide future efforts to ensure success, treats causes rather than symptoms, and not waste money repetitively on ineffective measures or actions that actually increase erosion and sediment yield. It is essential to involve local land managers in the adaptive management process to promote local and regional knowledge and expertise.

5 The Need for Best Management Practice (BMP) Guidelines for Alluvial Gully Erosion on Grazing Lands

In the context of soil conservation and erosion, Best Management Practices (BMPs) and Worst Management Practices (WMPs) exist as two end members of possible land management scenarios on the ground to address the physical, biological, environmental, economic, social, and cultural uses, needs, and conservation of soil resources.

Best Management Practices (BMPs) can be defined as:

- Those land management practices and activities that stop, reduce, or minimise existing or future soil erosion by retaining soil particles at their source through various physical, chemical or biological measures.

Worst Management Practices (WMPs) can be defined as:

- Those land management practices and activities that directly, or due to negligence or inaction, accelerate or enhance existing or future soil erosion.

Currently there is a lack of awareness among landowners and managers in northern Australia as to the relationship between land-use practices and alluvial gully erosion, let alone knowledge about how to minimise and manage alluvial gully erosion via BMPs. Across northern Australia, many WMP's are still being conducted around concentrated areas of alluvial gully erosion, such as overgrazing, lack of wet season spelling, poorly placed, installed and managed fences and roads, lack of off-stream water points, inappropriate fire regimes, lack of weed management, dumping rubbish and tyres in gullies, mechanically regrading gullies without revegetation BMPs, etc. (e.g., Winter 1990; Shellberg 2011).

A prerequisite for farmers and graziers changing their land management practices to achieve sustainability is the awareness of the natural and anthropogenic issues leading to land degradation, and the knowledge of the pathways, tools, and funding of how to reduce erosion via altered practices. In the absence of government intervention or regulation, the best way to change a farmer/grazier/operator's practices is to involve them in realistic field trials of how sustainable practices and rehabilitation can be achieved. This is currently being conducted through the cost-share program of Reef Rescue with local landowners in the Normanby and other catchments. However, specific and robust BMPs to reduce alluvial gully erosion are lacking to complement this Reef Rescue effort. Detailed on-the-ground expertise is also lacking from teams of seasoned soil conservation specialists. Furthermore, and possibly most importantly, the level of funding needed to implement effective BMPs at the cumulative catchment scale to reduce alluvial gully erosion is grossly insufficient. Economic, political and social issues will be discussed in Section 8.

Comprehensive BMPs to address alluvial gully erosion need to be developed from the outcomes of trial rehabilitation programs conducted in multiple catchments with alluvial gullies (e.g., Normanby, Mitchell, Burdekin, Fitzroy, Gilbert, Leichhardt, Victoria, etc.). This effort is likely to take up to a decade to come to full fruition as funding, implementation, monitoring, reporting and synthesis all take considerable time. More widespread trials and BMPs outcomes should also be founded upon local land manager and practitioner knowledge, as well as existing literature and practical knowledge on gully erosion control from other regions of Australia and the world. However to date, generalised BMP guidelines for colluvial or hillslope gully rehabilitation in southeast Australia (e.g., Bartlett 1991; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008) are not directly applicable to alluvial gullies in northern Australia, which can involve different forms and processes (Brooks et al. 2009; Shellberg et al. 2013a). Furthermore, existing generalised BMPs for grazing land in northern Australia are not specific enough to address the complexities of managing alluvial gully erosion initiation or reduction (e.g., Coughlin et al. 2007; 2008). However, several soil conservation manuals developed in northern Australia (Hadden 1993; Jolley 2009) have made important contributions toward the development of BMPs for alluvial gully erosion control.

The specific steps needed to develop a comprehensive, regional, Best Management Practice (BMP) manual to address alluvial gully erosion are as follows:

1. Review up-to-date local and regional knowledge and literature on alluvial gully prevention and rehabilitation (where it exists)
2. Quantify economic/environment costs, benefits, obstacles and solutions for gully rehabilitation efforts, changes in land management, and grazing paradigms.
3. Secure funding for decadal scale alluvial gully rehabilitation trials in multiple catchments in northern Australia
4. Design appropriate rehabilitation actions and techniques to prevent or rehabilitate alluvial gully erosion at selected sites and areas
5. Implement both indirect/passive and direct/intensive measures to prevent or rehabilitate alluvial gully erosion at selected sites and areas
6. Involve local land managers in the design, implementation and outcomes of the trials
7. Design implementation and monitoring programs using a before-after, control-impact (BACI) study design that builds off rigorous scientific methods
8. Report on project components and overall outcomes by sub-region or catchment
9. Synthesise regional gully rehabilitation trial outcomes and scientific data into a BMP manual via workshops
10. Involve regional landowners and stakeholders in the development of the BMP manual via workshops, interviews and field days.
11. Develop a communication strategy aimed at tailoring communication outputs to target audiences (landholders, managers, stakeholders).
12. Produce printed and multimedia educational products for dissemination to stakeholders across northern Australia.
13. Distribute BMP guidelines and education products to stakeholders through a broad range of existing networks and media.
14. Undertake follow-up surveys via phone, email, or in person regarding the uptake of information about alluvial gully erosion, rehabilitation, and BMPs in northern Australia.
15. Develop additional targeted educational outreach programs to stakeholders such as seminars, workshops, and regional land-use conferences.
16. Continue future collaboration and monitoring where fruitful and reasonable.

This two-year pilot project in the Normanby catchment is an initial step towards this BMP development.

6 Prevention of Alluvial Gully Initiation on River Frontage Grazing Land

The most practical and economical solution for gully management is to not initiate or accelerate alluvial gully erosions in the first place by using sustainable land use and grazing practices. Once started, large alluvial gullies are difficult and costly to repair. It is also cheaper to address newly formed gullies before they develop into large ones. In all aspects of gully management, where possible, the key is to address and remove the actual causes of accelerated gully erosion (base level changes, soil erodibility, reduction in vegetation cover, cattle disturbance, excess water runoff, water concentration along cattle tracks (pads), road and fence placement and maintenance, etc.), rather than addressing just the symptoms (the gully itself). Removing or addressing the original cause of erosion may not stop the gullying process once initiated, but it should slow down the process and make sure that any other gully treatments are not threatened. Options for preventing gully initiation will be reviewed here. Gully rehabilitation options are included in Section 7.

6.1 Principles of Gully Erosion Prevention

There are three main approaches to prevent gully initiation, as well as reduce gully erosion once started, which generally should be used in combination (Heede 1976; Lal 1992; Haigh 1984; Thorburn and Wilkinson 2013).

- Reduce water runoff into and through gullies and drainage hollows.
- Stabilise gully headcuts, sidewalls, and drainage hollows with vegetation resistance and/or physical structure.
- Reduce the gully channel slope and increase roughness using vegetation and grade control structures and/or which will trap sediment and promote revegetation.

For alluvial gully prevention, large-scale land management actions should directly or indirectly focus on:

- Increasing perennial grass cover above gully prone areas such as steep river banks.
- Reducing water runoff toward gully prone areas by improving soil/vegetation hydrologic functions upslope.
- Reducing concentrated water runoff down cattle tracks (pads), roads, and fences.
- Increasing perennial grass cover within gully prone areas to resist erosion and trap sediment.

These basic land management goals will help cumulatively prevent or reduce gully erosion in high risk areas such as sodic soils along river frontage and aid in indirect/passive long-term landscape rehabilitation. To accomplish this, a paradigm shift is needed for altered management of cattle movement and grazing patterns, fire regimes, weed control and spread, road and fence placement and management along river frontages. These topics and associated literature will be reviewed below in detail in regards to gully prevention.

6.2 Literature Review on Vegetation Cover and Gully Initiation

Vegetative cover in the form of grass, shrubs and trees and organic detritus (mulch) plays a protecting and stabilizing role for soil, predominantly reducing soil erosion. Roots increase the cohesion of soil and resistance to erosion; near-surface vegetation and mulch protect the soil from raindrop impact and increase the resistance to overland flow velocities; deeper roots of overstorey trees reduce the potential for mass movement (Thornes 1990; Gray and Sotir 1996; NRCS 1992). Vegetation also plays a mediating role in the hydrological cycle by intercepting precipitation, increasing actual evaporation, transpiring soil water and possibly groundwater, increasing infiltration through root networks and soil amended with organic material, decreasing water runoff, and increasing the storage of water in small depressions due to surface roughness (Penman 1963; Eamus et al. 2006).

For grassland and woodland savanna biomes, the vegetative ground cover on the soil surface and associated root biomass plays the most important role in soil protection and erosion resistance. The kinetic energy of raindrops is moderated by ground cover such as the leaf and stem structure of grass and/or the residue organic matter (mulch) remaining after senescence. This ground cover reduces the effective energy available at the soil surface to detach soil particles (Wischmeier and Smith 1978; Thornes 1990; Marston and Dolan 1999) by either direct drop splash or raindrop-induced flow transport (Ghadiri 2002; Kinnell 2005). Without ground cover, the high erosivity of rainfall in the Australian tropics (Yu 1998; Shellberg et al. 2013a) and beyond can directly impact the soil surface at full energy, which subsequently 1) breaks down soil aggregates, 2) dislodges soil particles by direct splash transport and/or indirect onward transport by sheet or concentrated flow, and 3) creates soil surface seals and crusts from dislodged clay particles. The latter can provide transient protection from further raindrop impact (Kinnell 2005; Walker et al. 2007). However, on exposed soils and particularly sodic soils, the loss of aggregate stability from both raindrop impact and soil dispersion can create surface seals, crusts and scalds, reduce infiltration rates, and promote sheet and concentrated flow that accelerates soil surface and sub-surface erosion (Sumner 1995).

Grazing animals in rangelands can reduce the grass ground cover, vigour, and diversity directly by consuming, trampling and shearing vegetation, and/or indirectly via soil compaction, loss of soil organic carbon, reduced infiltration and soil water availability, and indirect changes in species presence/absence or dominance (Trimble and Mendel 1995; Evans 1998). The loss of cover from grazing in addition to other factors such as drought have resulted in serious pasture and land degradation in Australia (McKeon et al. 2004; Stafford Smith et al. 2007).

In rangelands, the loss of ground cover from grazing has been correlated to a decrease in water infiltration, increase in water runoff, and increase in surface soil erosion and sediment yield (Tunstall and Webb 1981; Bridge et al. 1983; Greene et al. 1994; McIvor et al. 1995; Scanlan et al. 1996; Roth 2004; O’Reagain et al. 2005; Dunne et al. 2011; Bartley et al. 2010a; 2010b; O’Reagain and Bushell 2011; Silburn et al. 2011). Often but not always, thresholds of vegetation cover exist below which major soil erosion can occur. Thus is typically ~ 50% cover as a minimum threshold (McIvor et al. 1995; Evans 1998). Many studies document significant increases in water runoff and soil erosion with decreasing vegetation cover (McIvor et al. 1995; Scanlan et al. 1996; Silburn et al. 2011), while others define more subtle relationships (O’Reagain et al. 2005; Bartley et al. 2010a; 2010b; O’Reagain and Bushell 2011). For example, O’Reagain et al. (2005) documented few differences after 5-years in runoff and erosion from shallow hillslopes with different grazing intensities, but a treatment of complete cattle exclusion was not conducted. In later years however, significant differences in the volume, rate, and duration of water runoff and sediment and nutrient yield were measured (O’Reagain and Bushell 2011), indicating that recovery of soil and vegetation conditions with changes in grazing management can take considerable time. Roth (2004) documented that improved grass cover (>75%) over longer time periods (up to 15 years) is needed to improve hydrological function and reduce water runoff in northern Australian rangelands.

Current grazing BMPs suggest that ground vegetation cover (both live and dead) should exceed 50% cover at the ‘break-of-season’ (BOS) at the end of the dry season to reduce soil erosion and water runoff (McIvor et al. 1995; Scanlan et al. 1996; Evans 1998; Rolfe et al. 2004; Silburn et al. 2011). The exact timing of the BOS can be defined many ways (Balston and English 2009), but typically occurs in late-November or early-December in northern Queensland. Preferably, BOS vegetative cover should exceed 75% each year over many years to decades to improve hydrological functions (Roth 2004). To achieve > 50% vegetative cover in northern Queensland, on average 800 - 1000 kg/ha of dry pasture matter yield is needed at the end of the dry season (Rolfe et al. 2004). However, on more fertile alluvial and black soils this can be achieved with less biomass and depends on specific grass species and their growing habitats. A target of 800 - 1000 kg/ha of dry pasture matter yield on better soils could result in a yield towards the optimal target of > 75% cover.

Not all types of ground cover are equally efficient at reducing local erosion and water runoff. Dead grass mulch, leaves and sticks can be effective at covering the soil and reducing the effective energy of raindrop impacts on the soil. However, this material can be washed away during overland water runoff, such as with residual mulch of annual grasses. The attached living roots and tussocks of perennial grasses are more effective at binding the soil together through increased cohesion, increasing surface roughness, increasing water infiltration, and reducing water runoff. Perennial grass cover > 50 to 75% should ideally be used for targets and erosion reduction.

Once concentrated surface runoff occurs, vegetative cover such as perennial grass on down-slope areas can enhance the resistance of the soil to erosion through root cohesion (Gyssels et al. 2007; De Baets et al. 2006; 2007) and surface roughness (Prosser and Slade 1994; Knapen et al. 2009), which decrease soil erodibility and increase the critical shear stress needed for erosion, respectively (Knapen et al. 2007; Knapen and Poesen 2010). For the initiation of rills and gullies from concentrated overland flow, there are intrinsic thresholds of vegetative cover and root biomass beyond which a given shear stress from flowing water will erode a channel. Both Graf (1979) and Prosser and Slade (1994) provided empirical evidence that reduced vegetative cover or biomass for a given hydrological regime can induce gully erosion. Both natural factors such as drought and fire, and anthropogenic factors such as grazing, tree clearing, and fire regime changes can influence vegetative cover and thresholds of gully erosion. In Australia, grazing impacts from cattle and sheep have been documented to be major contributing factors in reducing vegetative cover, increasing runoff, and initiating gully erosion (e.g., Condon 1969; Eyles 1977; Prosser and Slade 1994; Prosser and Winchester 1996; McKeon et al. 2004; Pringle et al. 2006).

In terms of overall catchment sediment budgets, soil erosion from surface soils of rangeland hillslopes in northern Australia has been documented to be relatively small compared to subsurface sources such as gullies and bank erosion (Wasson et al. 2002; Bartley et al. 2006; 2010a; 2010b; Caitcheon et al. 2012; Brooks et al. 2013; Wilkinson et al. 2013; Olley et al. 2013). Regardless, hillslopes in northern Australia rangelands are the major sources of *water runoff* since they occupy the majority of the landscape area. Therefore, reducing water runoff volumes and velocities off hillslopes through improved management of vegetation cover and roughness could influence runoff into alluvial and colluvial gully areas below hillslopes, and thus the initiation or acceleration of gully erosion. However, where rocky hillslopes have been stripped of soil mantles, improved vegetation cover will likely have minimal effects on water retention due to a lack of soil storage potential.

The exact relationships between up-slope water production influenced by vegetative cover and down-slope gully erosion from runoff remains poorly quantified in Australian rangelands. On low-gradient alluvial floodplain slopes, Shellberg et al. (2013a) measured seasonal differences in alluvial gully scarp retreat driven by rainfall and floodplain water runoff, which he partially attributed to improved vegetation cover and reduced runoff coefficients in the latter half of the wet season. On colluvial hillslopes, detailed studies by Bartley et al (2006; 2010a; 2010b) documented 'reduced hillslope runoff for the first runoff events of the wet season' as a result of improved Grazing Land Management (GLM). However, they did not document changes in annual water runoff coefficients after 5-years of significantly improved but not ideal GLM conditions. No reductions in gully erosion rates were detected as a result of upslope improved GLM conditions and hydrological function; but their experiments also did not include trials of full cattle exclusion over the long-term, which would likely be needed for significant hydrological improvement of the soil and runoff reduction (Roth 2004).

6.3 Literature on Cattle Tracks (Pads) and Alluvial Gully Initiation

The erosional impact of introduced ungulate hooves (cattle, sheep, horses, etc.) on fragile Australian soils is well known (e.g., Russell and Isbell 1986). Cattle hooves create a static pressure on the soil that is up to six times that of macropods such as the kangaroo (Noble and Tongway 1986, reviewed in AGSO 1995) (Table 2). Furthermore, the sharp hooves of cattle can cut into the soil during trampling, while habitual migrations to grass feed and water can cut cattle tracks (pads) into the soil that concentrate water and accelerate erosion (e.g., Trimble and Mendel 1995; Dunne et al. 2011).

Table 2 Static foot pressures for a number of animals (data reproduced from AGSO 1995 and originally cited in Noble and Tongway 1986)

Herbivore	**Liveweight (kg)**	**Individual foot area bearing on soil surface (cm^2)**	**Static pressure per foot surface (kg/cm^2)**
Kangaroo	33-66	36	0.8-1.8
Sheep	40-55	21	1.9-2.6
Camel	450-650	411	1.1-1.6
Horse	400-700	184	2.2-3.8
Cattle	500-600	115	4.4-5.2

While vegetation cover management is essential along hillslopes and river frontage areas to reduce runoff and soil erosion and increase resistance to gully erosion, dense networks of active cattle tracks (pads) can concentrate water runoff and overwhelm any improved cover and roughness conditions (e.g., Figure 12; Figure 13). Daily migrations of cattle between 'river frontage' paddocks and in-river water holes can lead to dense and deep networks of cattle tracks created over decades (Condon 1986; 1988; Shellberg 2011; this report). Cattle tracks typically follow the easiest path to the river for water, which in many cases is down hollows or pre-existing bank gullies, resulting in heavy physical disturbance of these conditionally stable features (Shellberg 2011). Deep cattle tracks worn into steep river banks, hollows and pre-existing bank gullies can cut into highly erodible dispersive or sodic sub-soils and initiate alluvial gully erosion (Condon 1986; 1988; AGSO 1995; McCloskey 2010; Shellberg et al. 2010; Shellberg 2011; this report). Positive feedback mechanisms can then enhance the development of alluvial gullies, as accelerated water runoff from reduced vegetative grass cover can funnel into cattle tracks and incipient gullies, promoting incision, headcut retreat and alluvial gully evolution (Brooks et al. 2009; Shellberg 2011).

Condon (1986) summarised the influence of cattle migrations and tracks (pads) on the initiation of alluvial gullies in river frontage country "*[alluvial] gullies have been initiated from cattle pads over the high bank in earlier times when there would have been large concentrations of cattle watering on the rivers after the small waterholes in the backcountry had dried up towards the end of the dry season. Once channelized flow had reached the B horizon, the rate of down cutting and side cutting would be very rapid in these highly dispersible clay soils*."


a) b)

Figure 23 Cattle tracks (pads) funnelling water, sediment and debris off floodplain landscapes toward gully heads.

More detailed scientific research is needed into the more precise mechanisms of gully initiation and acceleration from cattle tracks (pads). Studies are needed on animal migration routes and patterns via tracking, vegetation cover influenced by grazing along tracks, water runoff acceleration along tracks, subtle water flow paths across floodplain flats and hollows, cattle track concentration down pre-existing gully features, and the potential to revegetate and infill existing cattle tracks over time through cattle exclusion. See Section 7.5.2.1 and 0 for more information on cattle track locations and cattle exclusion.

6.4 Manuals on Grazing Land Management

Grazing land management (GLM) manuals have been developed in northern Australia that outline best management practices (BMPs) to reduce water runoff, soil erosion, and land degradation. These objectives can be achieved by retaining good perennial grass cover and vegetation on slopes and riparian zones through proactively managing grazing intensity, fire, weeds, roads and fences. However, they only partially address some of the management issues surrounding gully initiation and prevention, especially for the complex issues surrounding alluvial gullying on river terraces and floodplain levees.

In Queensland's Burdekin catchment, grazing land BMPs have been developed to improve water quality and reduce sediment pollution in river systems (Coughlin et al. 2007; 2008). Managing both upland and river frontage country are covered in detail in relation to water quality. BMP recommendations are provided for fencing to land type; fencing river frontage; spelling/pasture rest; vegetation cover targets; fire regimes; off-stream watering points; road (track) management; monitoring; and basic gully management. The concept and problem of alluvial gullying along river frontage were reviewed in these manuals and basic principles such as fencing these areas off from cattle were recommended. However, the fencing recommendations were often too close to gullies – often with ongoing season grazing internal to river frontages – and did not appreciate the large areas of erodible terrace and floodplain margins that need to be managed to reduce water runoff into alluvial gullies on banks.

The Queensland Department of Primary Industries has produced several 'Grazier's Guides' to '*Managing Grazing in Northern Australia*' and '*Managing Northern Speargrass*' for reducing pasture and land degradation and improving profitability (Partridge 1995; 1999). The guide to managing native black spear grass (*Heteropogon contortus*) country (Partridge 1995) is very applicable to the upper Normanby catchment, the northern limit of the species and pasture community. Topics covered include the decline in *Heteropogon contortus* and *Themeda triandra* with heavy grazing and replacement with Indian Couch (*Bothriochloa pertusa*); property planning by land type; stocking rates and adjustments seasonally and during drought; pasture condition and monitoring; safe pasture utilization of 20-25% summer pasture yield; seasonal spelling for pasture health; burning every 3-4 years for pasture health and woodland thickening; weed control and pasture improvement; and cattle feed, health and productivity. Overgrazing on river frontage country with erodible dispersible clays is highlighted, but strong recommendations are lacking to fence stock out of these areas to reduce gully erosion.

The Queensland Government Report "*Managing Grazing Lands in Queensland*" (QDERM 2011) reviewed holistic management principles for improved soil conservation on grazing lands. They reviewed causes of land and pasture degradation; pasture management and utilisation rates; stock rotation and climate variability; use of fire for pasture and woodland management; fencing to land types; off-stream water points; ground cover and soil conservation; gully erosion; erosion along roads, fences and dams; scald reclamation after loss of ground cover; biodiversity weed and pest management; riparian vegetation; salinity and water resources. For gully erosion, they emphasised the importance of maintaining good ground cover upslope of gullies, fencing off gullies from cattle to promote revegetation, and replanting vegetation in gullies, rather than costly engineering intervention. Managing water runoff down roads and fences was also emphasised. Preventing gullies from occurring was stressed as a better option than controlling them once initiated (QDERM 2011).

As another example in the Northern Territory, several BMP manuals have been produced for and by the grazing industry to guide the management of cattle and land (NTG 2009; 2013). Topics range from animal health, management, and nutrition; station infrastructure such as roads, fences and dams; and pasture and land management such as cattle rotation, pasture health, weeds, and fire. However, very little information is provided on erosion control except along graded roads and fences; and gully erosion is scantly mentioned (NTG 2009; 2013).

More generic, Australian-wide guidelines have been developed for managing cattle and stock along waterways to improve water quality and river health (Staton and O'Sullivan 2006). These guidelines cover controlled grazing, fencing river frontage, fencing types, stock access points, flood fences, watering systems, regenerating riparian vegetation, and overall property planning. However, gully erosion is only addressed briefly.

6.5 Grazing Land Management on River Frontage to Reduce Alluvial Gully Erosion

“*Inappropriate and excessive stocking rates are probably the most common causes of deteriorating pasture conditions and soil degradation*” (Pressland et al. 1988). To reduce the initiation or acceleration of alluvial gullies, cattle grazing rates, duration and timing need to be carefully managed on terraces, elevated floodplains and steep banks of river frontage country with dispersive or sodic soils. Alluvial ‘river frontage’ areas include 1) the relatively flat catchment areas of alluvial terraces, elevated floodplains and hollows (swales) that subtly drain water toward the breaks in slope of stream/river banks, 2) the high and low banks of streams/rivers where alluvial gullies initiate, and 3) the overall riparian vegetation zone that changes along a gradient from the stream channel to the high floodplain or terrace (Figure 27).

Alluvial soils along river frontages in northern Australia are currently (and were historically) preferentially grazed by cattle due to access to water and improved forage production. For example, average cattle grazing densities for Cape York Peninsula are very low (~ 1 beast/40 ha on average), while productive properties have modest densities (~ 1 beast/20 ha), and river frontages can have the highest densities (>1 beast/10 ha) (Edye and Gillard 1985; Cotter 1995; Arnold 1997). The resultant heavy grazing pressure in river frontage can result in a decline in pasture condition, enhanced weed invasion, dense networks of cattle tracks (pads) over steep banks to access water, and resultant soil and gully degradation (Condon 1986; Pressland et al. 1988; Scattini et al. 1988; Rolfe et al. 2004; Shellberg et al. 2010; Shellberg 2011; Section 2). Sodic soils along river frontages are often textural contrast duplex soils, typically with a thin A-horizon of topsoil that overlies massive sodic sub-soil clays that are highly dispersive and erodible (Isbell et al. 1968; Galloway et al. 1970; Biggs and Philip 1995a; 1995b; AGSO 1995; Shellberg 2013a). Once these topsoils are disturbed, degraded or cut into, scalding and alluvial gully erosion can result. Weed invasion from a combination of sources into over-grazed and degraded river frontage soils also can result in pastures with little grazing value, but some vegetation cover (Rolfe et al. 2004). However, often the vegetation cover, root cohesion, and hydrological function of weeds are inferior to that of native, deep-rooted, perennial grasses.

To prevent gully initiation and promote gully rehabilitation along river frontages, a combination of grazing management actions is needed to reduce grazing pressure, reduce cattle track (pad) density and depth, and improve perennial grass cover and health. These actions include: managing for vegetation cover targets, fencing river frontage areas and associated terrace catchments with dispersive or sodic soils, wet season spelling, full cattle exclusion in highly erosion prone areas, off-stream water point development, traditional (alternative) fire regimes, weed control, more considered placement and maintenance of fences and roads. These will be reviewed below.

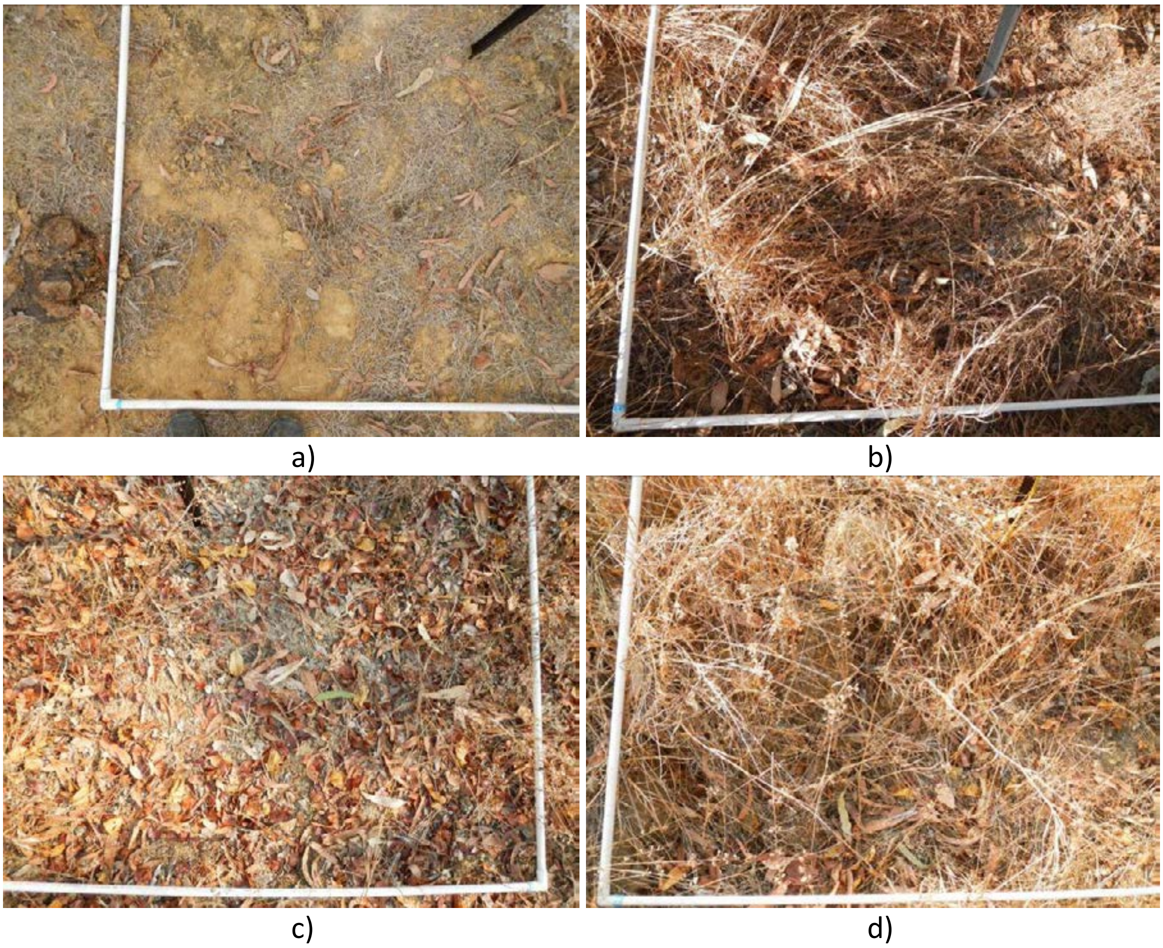
6.5.1 Vegetation Cover Targets on River Frontage with Dispersive or Sodic Soils

A ‘break of season’ (BOS) vegetation cover target of > 75% cover should be managed for to ensure good perennial grass cover (4P, perennial, productive, palatable, <u>protective</u>) and hydrological functions for river frontage areas of alluvial floodplain and terraces, floodplain drainage hollows, and especially steep river banks prone to alluvial gully erosion. This level of BOS cover needs to be sustained for many years to decades on average to maintain hydrological and erosion resistance functions (Roth 2004). Annual variability in rainfall, fire frequency and native and exotic grazing intensity obviously will need to be taken into account with vegetation targets, but 75% cover should be the average vegetation cover target at the decade time scale. While lower minimum vegetation cover targets (40-60%) have been suggested by others for hillslope soils (McIvor et al. 1995; Scanlan et al. 1996; Evans 1998; Rolfe et al. 2004, Coughlin et al. 2007; 2008; Karfs et al. 2009; Silburn et al. 2011), more conservative vegetative cover targets are needed for highly dispersive or sodic soils along river frontage.

For vegetation cover evaluation, native perennial, productive, palatable, protective (4P) grass species should be emphasised for cover management targets. In the upper Normanby catchment, key native grasses include black spear grass (*Heteropogon contortus*) and kangaroo grass (*Themeda triandra*), and even the less palatable but very erosion resistant blady grass (*Imperata cylindrica*) (Weston 1988; Neldner et al. 1997; Partridge 1995). In the lower Normanby catchment, there are many native perennial grasses in the Schizachyrium community that provide good 4P cover [*Sorghum plumosum var. plumosum; Dichanthium sericeum* (Queensland Blue grass)*; Capillipedium parviflorum* (Scented Top grass)*; Eriachne spp.*) in addition to important native annuals (*Themeda arguens* (Christmas Grass)*; Panicum spp.; Eriachne spp.; Schizachyrium fragile* (Firegrass)](Weston 1988; Neldner et al. 1997). Some introduced exotic perennial pasture grasses can also be suitable for good 4P vegetative cover and effectively binding the soil together such as Indian bluegrass (*Bothriochloa pertusa*) and sabi grass (*Urochloa mosambicensis*). The introduced pasture species ‘wynn cassia’ (*Chamaecrista rotundifolia*) is palatable and productive, but not an obligate perennial or deep-rooted and thus poorly binds the soil together despite abundant cover and mulch. Wynn cassia can also outcompete and reduce 4P grasses, leading to pasture degradation and the need for weed control in the long run (O’Gara 2005). While dead matted grass and leaves and sticks do provide soil cover for rainfall protection, it is the deep-rooted perennial grasses that provide erosion resistance and improved soil hydrological functions.

Vegetation cover and other associated metrics should be regularly monitored in river frontage paddocks and riparian zones subject to cattle grazing. Annual monitoring of cover at the BOS (November) is important to determine cover conditions going into the first storms of the wet season. In practice however during active grazing, monitoring cover will need to occur at several points in time through the dry-season to ensure that grazing pressure does not exceed the ability to meet BOS (November) vegetation cover targets.

Vegetation cover and other associated metrics should be consistently monitored at fixed plot locations (stable star pickets) scattered across the river frontage paddocks and riparian zones of cattle properties. A sufficient number of plots are needed to represent the spatial variability of landform (steep banks, flats, hollows, and gullies) and vegetation conditions across the river frontage, with the number of plots scaling to the size of the area. Protocols and metrics for permanent vegetation plot establishment and measurement of vegetation cover and other relevant variables are included in Appendix 10.1 and 10.2.



a) b)

c) d)

Figure 24 Examples of November ‘break of season’ (BOS) grass cover along riparian zones of the Normanby catchment: a) poor perennial grass cover (20%), low standing biomass (<<250 kg/ha), but moderate total cover (60%) from matted annual grass as a result of grader grass invasion and over-grazing, b) good perennial grass cover (65%), total cover (80%), high biomass (1100 kg/ha) and good root structure from native kangaroo grass (*Themeda triandra*), c) poor perennial grass cover (10%), low standing biomass (<250 kg/ha) with little root cohesion but good tree leaf cover (80%), d) fair perennial grass cover (30%), standing weeds (30%) and biomass (600 kg/ha) but dominated by weeds with poor root cohesion (*Hyptis suaveolens* and *Themeda quadrivalvis*).

6.5.2 Cattle Rotation and Seasonal Spelling

Historically on large breeder properties in northern Australia (e.g., Mitchell, Normanby, Victoria catchments), introduced cattle herds had accesses to large areas of grass woodlands where they could choose the best feed and watering location. These conditions and locations changed seasonally with the wet, dry, and shoulder seasons, and resulted in animals naturally selecting optimal grazing locations across space and time. As a result, grazing pressures were rotated across properties reducing the impact on specific local areas.

The major exception to this was the natural concentration of cattle along ‘river frontages’ for water and feed both historically and currently (Condon 1986; 1988; Pressland et al. 1988; Scattini et al. 1988; Winter 1990; Shellberg et al. 2010; Shellberg 2011; Barber et al. 2012; Barber et al. 2014). Alluvial topsoil along river frontages was often more fertile than backcountry floodplain soils or shallow rocky soils on hillslopes, despite being sodic at depth. Cattle concentrated on these topsoils to access nutritious feed, as well as water in rivers and streams. Naturally high ground along old river levees on floodplains and terraces also were favoured by cattle to escape floodwater but still have access to feed and water. The concentration of cattle along river frontages and daily migrations to the river for water over steep banks resulted in reduced vegetation cover from overgrazing, pasture degradation, dense cattle tracks, stripping of the A-horizon and exposure of sodic sub-soils, and the initiation and acceleration of alluvial gullies in sodic sub-soils (Condon 1986; 1988; Rolfe et al. 2004; Shellberg et al. 2010; Shellberg 2011; Section 2).

In more recent times, property infrastructure development intensified with the use of fencing to create medium and large paddocks for breeder management, along with installation of artificial water points and supplemental feed points to spread cattle grazing pressures across a given paddock. Thus, cattle migrations and grazing intensity became more restrictive to internal areas within a given paddock. Often this intensification resulted in pasture, soil and land degradation (Pressland et al. 1988) unless more progressive rotational or cell grazing practices were introduced (Bohnet et al. 2011).

The locations and configurations of fenced paddocks on properties can be quite variable depending on purpose and foresight. Some paddocks were created in an ad hoc, makeshift fashion, with little forethought (Pressland et al. 1988). Better designed paddocks followed natural boundaries such as ridgelines or rivers, while still others systematically divided grazing country up into manageable units with a range and diversity of pasture and water resources. River frontage areas were either 1) included as a component of a larger paddock so that cattle could access river water and pasture resources in the back country, or 2) fenced as discrete (riparian) paddocks themselves with fences on one or both sides of the river. In the latter case these riparian fences were often installed for the ease of seasonal cattle mustering rather than protection of riparian ecology. Alternatively, riparian paddocks were constructed as just another paddock that could be used as a late season reserve after other paddocks and water points had desiccated. Rarely was fencing installed to fully enclose sections of river frontage that included the full suite of habitats along the transition from the river, to low and high banks, and across the contributing catchment area of high floodplain or terrace that drains toward steep banks and gullies (Figure 2; Figure 27).

Bohnet et al. (2011) describes four distinct groups of graziers in the Burdekin Catchment based on their land and cattle management strategies: 1) Cell Graziers, 2) Rotational Graziers, 3) Continuous Graziers, and 4) Heavy Continuous Graziers. All these categories also exist in the Normanby catchment, but larger grazing properties typically follow a continuous to heavy continuous grazing regime with episodic rotation depending on rainfall patterns and grass availability. The use of each land management strategy depends on physical constraints such as land type, property size, water availability and infrastructure, but is also heavily dependent on several social and economic factors such as age/gender, family history, finances/off-farm income, income/debt, social norms/values, and perceived benefits/costs (Bohnet et al. 2011).

Most commonly in the Normanby and other catchments in northern Australia, large breeder paddocks are managed under a continuous grazing ‘set stocking’ regime. Cattle stocking rates are calculated on the annual carrying capacity of the pasture and available water at natural and artificial points, while supplementary feed is used to replace seasonal imbalances in nutrition, and the paddock is rarely rested. Depending on exact management and the degree that stocking rates exceed long-term carrying capacities, this type of grazing system can result in native pasture degradation over the long term, including soil erosion and gully initiation and acceleration, especially on river frontage country. Often introduced pasture species are added to help offset trends in pasture degradation (Miller et al. 1988) and nutrient deficiencies of pasture species (McLennan et al. 1988). This can have mixed results and in some cases promote further native pasture degradation or land condition change (i.e. soil acidification, nutrient depletion, fire or lack thereof, species change and weed invasion, soil erosion) (Noble et al. 2000). Heavy stocking at set rates is not profitable or sustainable in the long run (O'Reagain and Bushell 2011).


a) b)

Figure 25 Differences in grass cover on a) the over-grazed (left) and partially grazed (right) sides of a fence in the dry season and b) the grazed (left) and un-grazed (right) sides of a fence in the wet season.

Rotation grazing involves more proactive movement of cattle between paddocks over different time scales so that individual paddocks are rested and pasture species are allowed to recover before being grazed again (Briske et al. 2008; Teague et al. 2008). Stocking rates in any one paddock might be higher, but only for short periods of time (days to weeks to months). Rotational spelling can support the persistence of desirable pastures species, such as palatable, perennial, deep-rooted native grasses, especially if spelling timing coincides with the periods of early and main plant growth periods, flowering and seed set of grasses (e.g., wet season spelling in northern Australia; Pressland et al. 1988). This type of grazing system requires greater labour inputs needed to actively manage cattle, in addition to greater infrastructure such as paddock fencing and possibly a variety of improved pasture paddocks. However, long-term benefits from rotation and spelling can arise from animal weight gain, profitability and the sustainability of good pasture health (O'Reagain and Bushell 2011). Much debate exists on the exact style and detail involved with rotational grazing for a given landscape or paddock or feed sources (Rickert et al. 1988; Briske et al. 2008; Teague et al. 2008), with robust local data in the Normanby catchment still lacking on positive pasture rotation and restoration outcomes.

Wet season spelling through rotational grazing is critical for improved vegetation cover targets and native perennial pasture health in river frontage country. Wet season spelling allows for the protection of desirable perennial grasses during early establishment, growth and reproduction periods over the wet season (usually 3-6 months), and allows these desirable species to set seed to maintain future generations (Pressland et al. 1988). Wet season spelling can be conducted over different durations depending on the pasture species and can occur annually or periodically every 2-4 years to maintain long-term pasture health. Alternatively the timing of paddock spelling and grazing can be adjusted to manage desired and less desired species competition by resting preferred pasture species during their growth and seed cycles (Pressland et al. 1988) and targeting undesirable species at critical times to prevent seed set (e.g., weeds). Cycles of habitual animal migrations along specific cattle tracks and access points to water also might be broken by rotational grazing and wet season spelling. Wet season spelling regimes have been demonstrated to be as profitable as fixed stocking regimes, but with added long-term pasture health benefits (O'Reagain and Bushell 2011).

Rotational grazing and wet season spelling of river frontage country can be accomplished in many ways through more tactical grazing strategies that balance the long-term pasture, animal, and natural resource objectives. Other tools for improving the management and health of river frontage country include development of off-stream watering points, periodic use of fire to maintain the health, vigour and cover of perennial grasses, and weed control. These will be discussed below, along with the option of fully destocking fragile river frontage country where the erosion risk is extreme.

6.5.3 Reducing Stock During Drought Periods

The history of land degradation in Australian rangelands emphasises the importance of episodic destocking of sensitive areas during long dry seasons and drought years to retain natural resilience of grassland communities and their soil protection properties, and avoid major land degradation such as soil and gully erosion (Pressland et al. 1988; McKeon et al. 2004; Henry et al. 2007; Stafford Smith et al. 2007). This is especially true for dispersive or sodic soils along river frontages and riparian zones (Shellberg 2011). Seasonal, annual and decadal climate variability is a natural part of the Australian landscape, including the monsoonal landscape of Cape York Peninsula (Lough 1991; Nott et al. 2007; Shellberg 2011). The erosional impacts of these climate variations can be exacerbated by overstocking during drought and not adjusting herd numbers quickly enough to respond to changing conditions.

Forecasting climate variability is now a regular occurrence, albeit with some uncertainty (http://www.longpaddock.qld.gov.au/). These forecasts can be used by pastoralists to adjust stocking levels while also maintaining a profitable business (e.g., O'Reagain and Bushell 2011). Pressland et al. (1988) recommended pastoralists should rapidly decrease stock numbers when summer rains are below average and forecasts are bad, rather than maintain numbers through the dry into the next wet in the hope of good rain. The conservative sale of stock in good condition in anticipation of drought will save money, rather than incurring drought-induced losses and expenses such as feeding supplements for extended periods. During the restocking of cattle, Pressland et al. (1988) recommended slow or delayed restocking of many paddocks to allow pastures to regain their vigour and promote seed recruitment. This could be accomplished by retaining residual herds in key resilient paddocks with supplemental feed until more sensitive paddocks have rested and recovered from drought conditions.

Figure 26 An over-grazed river frontage hollow after a drought (long extended dry season and below average wet season) in the Normanby Catchment. This hollow flows directly into a downstream gully (Figure 81a).

6.5.4 Full Stock Exclusion from River Frontage with Dispersive or Sodic Soils

In the most erosion-prone river frontage areas, the complete exclusion of cattle should be considered on a large scale to remove chronic soil and vegetation disturbance, such as consuming perennial grasses, compacting soil, and cutting deep cattle tracks (pads) along floodplains and over steep banks. Alternatively, spelling cattle from an erosion prone area over many years to decades could be used to allow pasture species and eroded areas to slowly recover before eventually being grazed again under an alternative regime (see Section 7.5).

For example, many river frontage margins on floodplains and terraces in northern Queensland have been mapped as regional hotspots of alluvial gully erosion (e.g., Figure 14; Figure 15; Figure 38; Brooks et al. 2006; 2009; 2013). These erosion prone alluvial floodplains and terraces typically coincide with sodic duplex soils that have a high percentage of exchangeable sodium (ESP) associated with massive clay sub-soils that easily disperse and erode once exposed. The locations of sodic soils have already been mapped during regional soil resource inventories by government departments (Isbell et al. 1968; Galloway et al. 1970; BRS 1991; Biggs and Philip 1995a; 1995b). These areas known to be at risk for alluvial gully erosion historically, currently or in the future could be managed to exclude or reduce cattle grazing pressure on vegetation, soil resources, and the initiation and acceleration of alluvial gully erosion. Reducing the erosional impact of station road and fence construction, use and maintenance could also be the result of destocking these erosion prone areas on a larger scale.

There are practical constraints to excluding or spelling cattle from large areas of river frontage over long periods of time due to infrastructure maintenance issues. This will be discussed below.

6.5.5 Strategically Fencing River Frontage with Dispersive or Sodic Soils

In order to accommodate either annual or periodic wet seasonal spelling or full stock exclusion of river frontage areas to reduce alluvial gully erosion, fences must be constructed and maintained to exclude domestic and wild cattle. The exact placement and extent of fencing highly depends on the configuration of the river frontage country and specific management needs and objectives. For example, large hotspots of alluvial gully erosion in the Normanby catchment (Figure 14; Figure 15; Figure 38) could be strategically fenced as large paddocks to spell or exclude cattle for large-scale erosion reduction benefits. Alternatively, individual pockets of alluvial river frontage along stream segments could be fenced for more localised benefits. In either situation, some general guidelines can be followed for fencing placement to reduce the initiation or acceleration of alluvial gully erosion.

There is a management conundrum between installing and maintaining fences to spell or exclude cattle from sensitive river frontage country to reduce alluvial gully erosion, and the real actual soil disturbance and gully erosion caused by the installation and maintenance of fences on and across sodic alluvial soils. Where fencing is deemed important to reduce gully erosion across small to large scales, fencing planning, installation and maintenance techniques need to take extreme caution to avoid accelerating or increasing erosion (Pressland et al. 1988), when the intent is to actually reduce it.

For fencing placement, it is critical to 1) fence by land type to ensure that alluvial gully catchment land units along the river frontage are protected, 2) to ensure the fence is placed in a location that will not actually accelerate rill or gully erosion during construction or maintenance, 3) to minimise the number of gully, stream and river crossings (i.e. flood gates) and 4) to allow for the simple maintenance of the fence over time while minimizing ground disturbance.

Fences parallel to the river on a floodplain or terrace should be located far enough back from the break-in-slope of the high bank so as to contain the relatively flat subtle catchment area of the floodplain that drains water toward the high bank and break-in-slope where alluvial gullies usually initiate (Figure 27). Fencing at or close to the break-in-slope of the floodplain and high bank can put the fence at risk from future gully erosion. More importantly it does not improve the soil and vegetation conditions in the subtle catchment areas above alluvial gully zones to reduce water and sediment runoff that can accelerate gully erosion. Ideally a fence should be placed at or beyond the catchment divide upslope of alluvial gullies. This will ensure that all major zones of the alluvial gully catchment are included in the cattle spelling or exclusion area (Figure 27). Where available, satellite aerial photographs and LiDAR topographic data can be used to identify subtle but important catchment divides on floodplains and terraces. Or alternatively at a larger scale, fencing could be placed on more easily identifiable bedrock ridgelines surrounding alluvial floodplain and terrace pockets on the landscape.

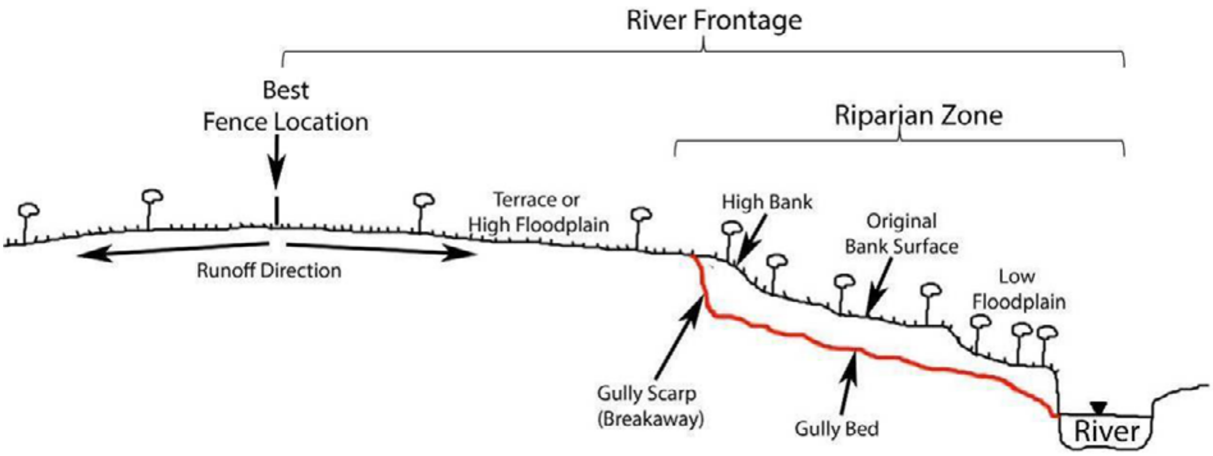


Figure 27 Cross-section drawing of an alluvial gully (bed and scarp) eroding into a high floodplain or terrace catchment from a steep river bank along the river frontage and riparian zone. Note the optimal cattle fence locations along the river frontage to reduce alluvial gully erosion. Note that the scale of river frontage and distance from the river to alluvial floodplain catchment boundary can be in the order of 1 to 3 km.

Proper planning of fence locations should include finding routes that minimise the number of fence crossings of existing gullies, unchannelled hollows, creeks, and rivers (e.g., flood fences). This will reduce maintenance costs and minimise the potential for rill and gully erosion often created along fence lines where they traverse steep banks at creek crossings. Satellite aerial photographs, LiDAR topographic data, and existing distribution maps of alluvial gullies (Brooks et al. 2006; 2009; 2012) can be used to identify the most appropriate locations for fences, in conjunction with more detailed field reconnaissance and route mapping to more precisely locate appropriate locations.

Where fences need to cross creeks or rivers, fence construction down steep stream banks on the approaches should utilise the ‘tree-to-tree’ construction technique without the need for grading or using fence posts on steep unstable banks (i.e. using live stable trees as wire strainer posts). Grading or bulldozing down steep banks at stream crossings to remove trees and vegetation will most often initiate and accelerate alluvial gully erosion. Similarly, machine grading grass vegetation along fence lines constructed on dispersive or sodic floodplains soils should be avoided, even on relatively flat areas, as this can accelerate overland runoff and initiate rill and gully erosion. Slashing or burning vegetation along fence lines without disturbing the soil is much less likely to accelerate erosion. Ideally, maintenance and clearing of vegetation along fence lines on sodic soils should utilise early-dry season fires (low intensity) to create fire breaks that will be effective later in the dry season to control large high intensity fires. This will minimise soil disturbance on sodic alluvial soils. However, fences would need to be constructed with durable fire-resistant steel to withstand periodic fires.

6.5.6 Off-stream Water Point Development

Artificial off-stream water points (surface ponds, dams across creeks, groundwater wells, windmills and troughs, etc.) for cattle can be important tools to decrease the grazing pressure and migration paths through riparian zones and river frontage to access water. Off-stream water points without associated fencing can be installed strategically several kilometres from rivers to draw cattle away from rivers. This can reduce the number of daily migrations cattle make across steep river banks, thus reducing cattle track (pad) density and depth and the amount of pasture vegetation consumed along migration paths.

More commonly, artificial off-stream water points are installed in association with fencing along riparian zones and river frontages, which allow for spelling or full exclusion of cattle from the river frontage. Water points are installed outside the river frontage fence in more distal paddocks that are retained for cattle production. Depending on adjustments to stocking density, these types of water developments can effectively increase the grazing intensity in areas around artificial water and reduce grazing within the river frontage, which would have positive and negative implications for local pasture condition and soil erosion in both locations.

Proper planning and placement of off-stream water points is essential to effectively reduce water runoff and soil erosion and balance trade-offs between development and soil conservation. Artificial water points are often sacrifice areas where ground cover is expected to be low, with high cattle tracks (pads) density (Pressland et al. 1988). Therefore placement of water points should be well away (> 1-2 km) from dispersive or sodic soils and breaks-in-slope prone to gully erosion on creeks and rivers (Figure 28). Artificial water points should be constructed beyond subtle alluvial catchment divides (ideal fence locations, Figure 27) that drain toward gully prone areas. This will ensure that surface water runoff from the more intensively managed areas around artificial water points does not flow toward steep river banks and promote alluvial gully erosion.

In many situations on terraces and elevated floodplains with sodic soils, surface water runoff from both sides of a shallow alluvial ridge (levee or subtle divide) promotes the potential for gully erosion. In extreme situations, these shallow alluvial ridges can be attacked by gully erosion from both the proximal and distal sides of the ridge (e.g., Figure 54; Brooks et al. 2009; 2012). Surface water runoff and gully erosion that drains distally away from the main river into smaller floodplain tributaries can still deliver large amounts of sediment to the river drainage network. Therefore, caution is needed when placing artificial water points and fences to ensure that these developments do not initiate or accelerate water runoff and gully erosion in distal portions of the floodplain or terrace (i.e., Figure 54; Section 7.5.2.4). In these situations, artificial water points and cattle exclusion fences should be placed well outside land types with dispersive sodic soils (terraces and elevated floodplains) to avoid erosion prone areas.

Figure 28 The poor placement of an off-stream water point (dam in background) in terms of erosion control due to high cattle impacts on sodic floodplain soils of an ephemeral creek and incising gully system.

6.5.7 Fire Regimes for Erosion Control on River Frontage with Dispersive or Sodic Soils

6.5.7.1 Fire Literature Review for Cape York Peninsula

Fire is a natural component of savanna landscapes (i.e., lightning) as well as a tool used and misused by Aboriginal and European people. Fire regimes must be carefully considered and prescribed burning must be tailored to soil type, vegetation community, annual weather patterns, and multiple management goals. The exact use of fire can be a contentious issue in northern Australia due to multiple and partially conflicting management goals, such as grass pasture health, woodland density, grazing, carbon sequestration, biodiversity, soil and gully erosion, weed management, bush food management, and traditional fire management. Often one or more of these issues will dominate how fire is used in a particular location. Unfortunately, soil and gully erosion is often the least considered issue, but has major long-term ramifications for terrestrial and aquatic habitats.

Few studies in northern Australia have made the direct or indirect connection between fire and erosion, and none have focused on gullying. Depending on the timing and intensity, fire can consume surface vegetation and organic cover, expose soils to the full force of tropical rainfall and runoff, and accelerate surface water runoff and erosion. Water quality and fire research from control and treatment hillslope catchments in the Northern Territory have demonstrated that high intensity late-dry season fires result in greater concentrations of suspended sediment from catchment erosion compared to early-dry season fires or fire exclusion (Townsend and Douglas 2000; Townsend et al. 2004). High intensity fires significantly reduced the ground and canopy vegetation cover that increased the catchments' vulnerability to erosion. Riparian vegetation diversity and density can also decrease with high intensity fires (Anderson et al. 2005). The longer time period between early-dry season burning and rainfall allowed for perennial grass regrowth prior to the wet season (e.g., Figure 30), and therefore reduced the risk of erosion (Townsend and Douglas 2000; Townsend et al. 2004).

Since European settlement and the introduction of cattle grazing on Cape York Peninsula, traditional Aboriginal fire regimes have been replaced by regimes that are tailored toward the production of cattle (Neldner et al. 1997; Crowley 1995; Crowley and Garnett 1998; Crowley and Garnett 2000; Russell-Smith et al. 2003; Drucker et al. 2008; Crowley et al. 2009). These regimes either 1) reduce fire frequency by restricting burning and heavy grazing of grass cover to reduce fuel loads, 2) focus on burning fire breaks in the early-dry season to protect remaining feed and control cattle movement, 3) burn in the early-dry season to promote grass regrowth and aid mustering, and/or 4) burn in the early-wet season (storm burns) to clear out old vegetation and weed biomass, reduce woodland thickening, maximise short-term cattle feed from grass regrowth, and promote long-term grass cover (Figure 29). In some areas of the Normanby catchment, heavy cattle grazing and fire suppression dramatically reduce fuel loads and fire frequency (near and south of the Lakeland/Cooktown highway, Figure 29). In other parts of the catchment, uncontrolled fires in the late-dry season are a result of a lack of proactive management and careless arson fires by hunters and tourists.

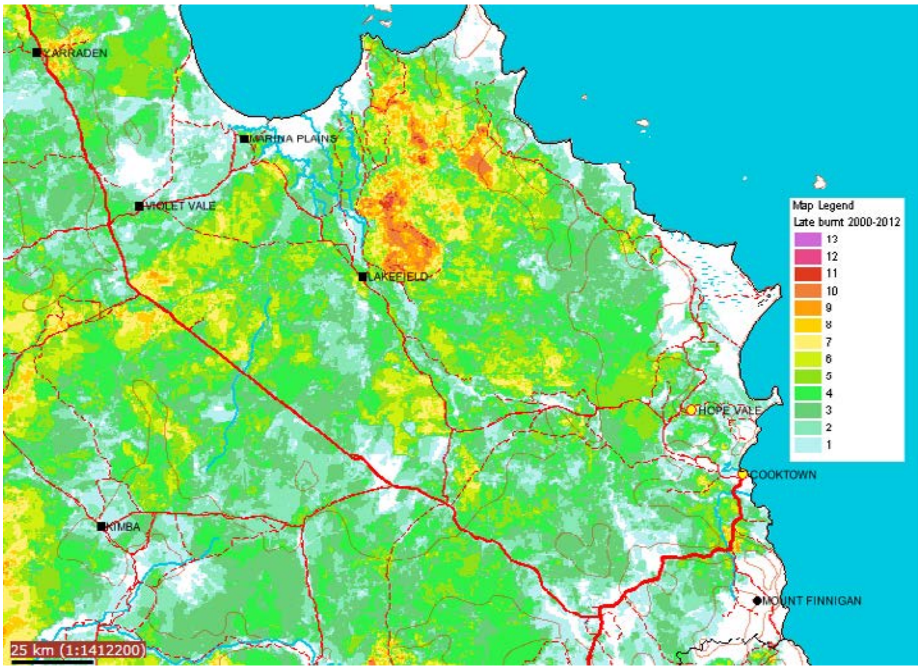


Figure 29 Pattern and frequency of intense late season fires (Aug-Dec) between 2000 and 2012 in the Normanby catchment (NAFI: North Australian Fire Information). The timing and distribution of all fires closely match those of late-season fires displayed here.

The river frontage margins of terraces and elevated floodplains represent transitional ecotones between riparian forests within river channels and higher elevation woodlands on river levees, terraces and bedrock hillslopes. Traditional Aboriginal burning on terrace and elevated floodplain flats would have occurred for various hunting and vegetation management purposes as part of a complex mosaic pattern of fire regimes across the landscape (Fensham 1997; Crowley and Garnett 2000; Standley 2011). While traditional aboriginal burning occurred throughout the year, fire burning efforts on terraces and elevated floodplains were likely concentrated around the early-dry season when these infrequently flooded surfaces began to dry out but sufficient moisture was available for regrowth of perennial grass (Fensham 1997; Crowley and Garnett 2000; Barber et al. 2012).

But the patch mosaic pattern and differential timing of Aboriginal burning would have resulted in river frontage patches not being burnt each year and in some years burnt during alterative seasons.

On many cattle stations historically in Cape York Peninsula, river frontage country was episodically burnt over space and time in the early- to mid-dry season to draw cattle onto young green grass shoots emerging after fire, which aided mustering, provided fire breaks, and improved the carryover of cattle through the dry season (Anderson et al. 1988; Crowley and Garnett 2000; Barber et al. 2012; Barber et al. 2014). If episodic river frontage burning and grazing was balanced and rotated with complementary efforts on ridges and tributaries in the backcountry, the fragile soils and ecosystems could be managed in a sustainable and economical way (Drucker et al. 2008; Barber et al. 2012). However over time, the pressures of grazing on river frontage country near water often exceeded the long-term carrying capacity of the grasslands, which contributed to the degradation of pasture health and soil and gully erosion (Shellberg 2011). Cattle often congregate on river frontage (e.g., terraces) for prime grass feed and access to water; and on active floodplains cattle often congregate on elevated levees near river banks and terraces to stay dry during the wet season, enhancing the degradation of these features (Condon 1986; 1988; Pressland et al. 1988; Scattini et al. 1988; Winter 1990; Shellberg et al. 2010; Shellberg 2011; Barber et al. 2012; Barber et al. 2014).

Along some river frontages and floodplains, dominance of some grass species over others, exotic weed invasion and various degrees/types of woodland thickening (e.g., *Melaleuca viridiflora*) resulted from overgrazing and altered fire regimes (e.g., Crowley and Garnett 1998; Crowley and Garnett 2000; Drucker et al. 2008; Crowley et al. 2009; Shellberg 2011). As pasture health and carrying capacity declined along river frontages and fences became more common to control cattle, many pastoralists shifted away from early-dry season burning toward a regime of fire prevention throughout the dry season in an attempt to maximise available cattle forage. Fires were subsequently lit in the early-wet season as intense 'storm burns' a few days after initial heavy rain (>25mm) for the purpose of clearing out remaining vegetation, reducing woodland thickening and promoting young grass shoots for cattle feed (Crowley 1995; Crowley and Trueman 2005; Drucker et al. 2008; Crowley et al. 2009). However, fire suppression also became problematic as high-intensity late-dry season fires (natural or deliberate) were hard to stop due to a lack of wide fire breaks from early-dry season fires and the ineffectiveness of narrow fire breaks along fence lines and station roads. On some stations, economic pressures to over-stock cattle and minimise spelling also reduced the effectiveness of the storm burn strategy, due to reduced fuel loads and spread or favouring certain weed species. Many pastoralists are currently rethinking fire regime paradigms, due to the economic costs of uncontrollable late-dry season fires, the fire break benefits of early-dry season fires over modest varying portions of their properties, and the use of a mixture of fire timing and cattle spelling to promote pasture health (Drucker et al. 2008; Crowley et al. 2009).

This synthesised knowledge of the ecological, cultural, social, and economic aspects of fire management on Cape York Peninsula has improved dramatically over the last few decades from the foundations of traditional indigenous, historic pastoral, and recent scientific knowledge (e.g., Crowley 1995; Fensham 1997; Crowley and Garnett 1998; Crowley and

Garnett 2000; Crowley and Trueman 2005; Drucker et al. 2008; Crowley et al. 2009; Standley 2011; Barber et al. 2012; Barber et al. 2014). Several management guidelines (e.g., Crowley and Trueman 2005; Reef Catchments 2011) and training workshops (e.g., Standley 2011; Traditional Knowledge Revival Pathways) have been developed to guide land managers and practitioners in the use of fire on pastoral, indigenous, and conservation properties. However, scientific research on fire regimes applicable to highly erodible sodic soils in river frontage has been minimal.

6.5.7.2 Specific Fire Regimes for Erosion Control on River Frontage with Dispersive or Sodic Soils

There are currently little rigorous quantitative scientific data on what specific fire regimes would be most appropriate to reduce water runoff, soil erosion, and the initiation or acceleration of alluvial gully erosion on river frontage woodlands and grasslands in northern Australia, especially on highly dispersive or sodic soils on alluvial terraces and elevated floodplains.

In some highly erosion prone locations such as gully fringes, fire should be excluded altogether (along with cattle management) to maximise ANY potential vegetation cover over the short-term, until longer term vegetation management strategies are developed for erosion control.

The highly erodible alluvial terraces of the upper Normanby-Laura catchment are on the northern fringes of the native black spear grass (*Heteropogon contortus*) pasture community (Weston 1988; Partridge 1995; Neldner et al. 1997) where kangaroo grass (*Themeda triandra*) was once more dominant, along with patches of blady grass (*Imperata cylindrica*). More recently black spear grass has reduced as introduced Indian bluegrass (*Bothriochloa pertusa*), grader grass (*Themeda quadrivalvis*), and many other weeds (e.g., *Hyptis suaveolens*) have invaded partially due to overgrazing. Specific fire and cattle grazing regimes need to be developed along these erodible river frontages to maximise perennial grass cover, minimise weed spread (e.g., grader grass, Keir and Volger 2006; Volger 2009), and promote perennial pasture health to reduce water runoff and soil erosion.

Kangaroo grass tends to flourish with early-dry season burns every 1 to 3 years, while black spear grass dominates with late-dry season fires every 3 years (Walker et al. 1983 in Pressland et al. 1988; Partridge 1995). Alternatively, early-wet season fires (storm burns) can also encourage kangaroo grass dominance (Pressland et al. 1981 in Anderson et al. 1988). For black spear grass (*Heteropogon contortus*), Partridge (1995) recommended burning every 3-4 years in the early-wet season (storm burns). Stocking at sustainable rates with spelling was also recommended to kept a good ground cover and allow black spear grass to drop seed, re-establish from new seedlings, and compete against weeds. Careful attention is needed to the growth cycles, plant tillering (offshoots), and seed production of native grasses when selecting prescribed fire regimes.

Restoring native black spear grass (*Heteropogon contortus*) pastures has been researched in detail (Orr et al. 1991; 1997; 2001; Orr and Paton 1997; Orr et al.; Orr 2004; Partridge 1995). Restoration can be accomplished by spelling cattle to build up full loads, burning in the early-wet season (storm burns) in one or more consecutive years to promote plant tillering and seed production, and then excluding cattle from overgrazing perennial grass regrowth and seed/tiller production after burning. Thus restoring good native pasture cover and vigour will take at least multiple cycles of seasonal cattle spelling and careful fire management.

For areas susceptible to erosion such as sodic soils, Anderson et al. (1988) recommended patch burns with low intensity fires no more frequent than every 3 years either in the early-dry season or early-wet season (storm burns). Early-dry season fires with some ground moisture will encourage the regrowth of native perennial grasses and often leave a layer of fine mulch and un-burnt grass that can protect the soil surface from early-wet season rainfall (Figure 30; Anderson et al. 1988; Townsend and Douglas 2000; Townsend et al. 2004). However, heavy grazing of perennial grass regrowth following early-dry season fires can reduce vegetative cover, which is needed reduce runoff and erosion during early-wet season rains (McIvor et al. 1995; Scanlan et al. 1996; Roth 2004; O'Reagain and Bushell 2011; Silburn et al. 2011). Frequent early-dry season burning and overgrazing by cattle can also reduce grass competition and lead to woodland thickening in the long term (Crowley and Trueman 2005).


a) b)

Figure 30 Examples of a) low intensity early-dry season burn in a colluvial hollow, and b) a perennial grass tussock and incompletely burnt mulch cover remaining after the low intensity burn.

Reef Catchments (2011) suggested that terraces and floodplains on Cape York Peninsula should be burnt in a mosaic pattern (30% un-burnt) on average every 2 to 5 years. A mix of both low-intensity early-dry season fires and higher-intensity early-wet season fires (storm burns) could be used, in combination with spelling cattle grazing to build up fuel loads and promote pasture health and seeding. Early-dry season fires using prescribed aerial and/or ground burning could be used to create large fire breaks to prevent intense late-dry season fires. However, using riparian zones and river frontage as early-dry season fire breaks every year or too frequently in the same location can exacerbate erosion through loss of perennial grass cover (Crowley and Trueman 2005). Cattle grazing should be managed cautiously through spelling or exclusion after early-dry season fires, so as to not overgraze perennial grass regrowth along river frontage in favour of weed or annual grass expansion. Crowley and Trueman (2005) and Reef Catchments (2011) recommend occasional moderate-intensity 'storm burns' in the early-wet season to kill tree seedlings and prevent woodland thickening [e.g., fires lit 2-3 days after the first heavy storm (>25mm of rain) in the early-wet season]. This is especially needed where *Melaleuca viridiflora* has invaded grasslands (Crowley et al. 2009), but may be less applicable to other vegetation communities. Storm burns in the early-wet season can also be used to manage weeds like rubber vine (*Cryptostegia grandiflora*). The influence of spreading other weeds such as grader grass with storm burns is less certain (Keir and Volger 2006; Volger 2009). From an erosion control perspective, the overall merits of moderate intensity storm burns in the early-wet season along river frontage remain questionable, due to the potential to reduce grass cover and expose soils to erosion for several weeks to a month at the beginning of the wet season (e.g., Townsend and Douglas 2000; Townsend et al. 2004).

Early-wet season 'storm burns' along river frontages with dispersive or sodic soils need to be conducted with extreme caution at a local scale to prevent accelerated erosion. Moderate to high intensity storm burns can remove all vegetative cover (live perennial grass, dead matted grass, leaves, sticks), scorch the soils and create hydro-phobic conditions, and expose erodible soils to intense tropical rainfall at the start of the wet season. Bare sodic alluvial soils are prone to surface sealing, scalding due to stripping of the A-horizon and loss of organic matter, reduced infiltration, and accelerated runoff (Rengasmy and Olsson 1991; Fitzpatrick et al. 1995; Naidu at al. 1995; Sumner 1995; Coventry 2004; Shellberg et al. 2013a). However, if major woodland thickening (e.g., *Melaleuca viridiflora*) or invasion of rubber vine (*Cryptostegia grandiflora*) has occurred along specific locations of erodible river terrace or floodplain along river frontage, the case could be made for tailored storm burns and cattle spelling regimes to be used as a restoration tool to reduce tree/shrub cover and increase perennial grass cover (Orr et al. 1991; 1997; 2001; Orr and Paton 1997; Orr et al.; Orr 2004; Crowley and Trueman 2005; Drucker et al. 2008; Crowley et al. 2009). Good perennial grass cover will be essential for reducing soil erosion in the long-term.

Balancing the needs of perennial grass health and cover, weed control, erosion control, cattle grazing, and fire management is complex and needs further research on alluvial frontage county and sodic soils prone to gully erosion in northern Australia.

6.5.8 Weed Management on River Frontages

In order to maximise the vegetative cover from native (or exotic) perennial pasture grasses (4P, perennial, productive, palatable, <u>protective</u>), exotic weed invasion and weed control must be diligently managed on river frontage floodplains and terraces. Weed invasion from a combination of sources into over-grazed and degraded river frontage soils can result in pastures with little grazing value, but some vegetation cover (Rolfe et al. 2004). However, often the vegetation cover, root cohesion, and hydrological function (e.g., infiltration) of weeds are far inferior to that of native, deep-rooted, perennial grasses. Thus weed invasion could promote accelerated water runoff from floodplain flats, reduce soil cohesion on steep river banks and hollows, and contribute to the initiation or acceleration of alluvial gully erosion.

Weed invasion into river frontages and riparian zones has become almost ubiquitous across Cape York Peninsula, except for areas least disturbed by man and cattle (Mitchell and Hardwick 1995; Neldner et al. 1997; Mackey et al. 1997; Rolfe et al. 2004; Waldron and Holznagel 2004; Keir and Volger 2006; Dunlop 2007; CYPPMAG 2007; Shellberg 2011; CSC 2012). The most notable river frontage and riparian weeds are rubber vine (*Cryptostegia* *grandiflora*) and more recently sicklepod (*Senna obtusifolia*) growing on river benches, steep banks and associated floodplain flats. On river frontage terraces, the tall herb mintweed (*Hyptis suaveolens*) and the exotic annual grader grass (*Themeda quadrivalvis)* have become the most common invaders of native perennial grasslands, but many others also are present (Appendix 10.6).

Depending on location and human/cattle disturbance history, many other exotic weeds have or could invade river frontages on Cape York Peninsula. For example, along the highly disturbed river frontage of the West Normanby River in and around alluvial gullies, 13 species of exotic herbs are present compared to 17 species of native herbs. Also, 6 species of exotic grass are present compared to 14 species of native grass (Appendix 10.6). Overall, 38% of the ground cover species were exotic and often dominated the overall cover and biomass. Notable deliberately introduced invaders are the pasture legumes 'wynn cassia' (*Chamaecrista rotundifolia*) and shrubby stylo (*Stylosanthes scabra*). Other less desirable weeds include mintweed (*Hyptis suaveolens*), hairy and spinyhead sida (*Sida trichopoda; Sida acuta*), snakeweed (*Stachytarpheta spp.*), and a variety of annual grasses (e.g., *Themeda quadrivalvis; Chloris inflate; Eleusine indica).* Sicklepod (*Senna obtusifolia*) has aggressively and fully invaded any open space along lower river benches regularly inundated by floodwater and not shaded by riparian trees.

In comparison on Crocodile Station in the disturbed 'Old Hay Paddock' on alluvial soils, 9 species of exotic herbs are present compared to 3 species of native herbs. Also, 5 species of exotic grass are present compared to 17 species of native grass (Appendix 10.6). Overall, 41% of the ground cover species were exotic and often dominated the overall cover and biomass. Grader grasses (*Themeda quadrivalvis),* mintweed (*Hyptis suaveolens*), shrubby stylo (*Stylosanthes scabra*), 'wynn cassia' (*Chamaecrista rotundifolia*), and hairy sida (*Sida trichopoda*) often dominated the exotic species cover.

In terms of alluvial gully erosion in the Normanby catchment, the loss of native perennial and annual grass cover (e.g., *Themeda triandra; Heteropogon contortus;* Schizachyrium community species) on steep river banks and hollows and their replacement by annual weeds and grasses (e.g., *Hyptis suaveolens; Sida trichopoda; Sida acuta*; *Themeda quadrivalvis)* likely induce major changes to the hydrologic function and erosion resistance of sodic alluvial soils. The roots of annual weeds are less effective at binding the soil together, especially at the beginning of the wet season. Associated weed changes to water infiltration and surface roughness on adjacent high floodplains and terraces that drain water toward river banks and hollows also could accelerate water runoff and gully initiation. Dominant annual herbs (*Hyptis suaveolens; Sida trichopoda; Sida acuta*) provide little ground cover protection early in the growing season and their shallow roots do not promote water infiltration or the build-up of organic matter. While aggressive annual grasses such as grader (*Themeda quadrivalvis*) can produce large amounts of biomass and provide much dead grass mulch cover by the end of the dry season, this residual biomass is highly prone to high intensity fires that can scorch and expose the soil surface and promote erosion (Keir and Volger 2006; Volger 2009). Annual grass roots also provide inferior root cohesion, surface roughness and water infiltration potential in the early-wet season compared to perennial grasses.

a) b)

Figure 31 Invasion of annual weeds into river frontage and riparian zones in the Normanby catchment a) dominance of annual herbs (*Hyptis suaveolens* and *Sida trichopoda*) and grasses (*Themeda quadrivalvis*) on river terraces, and b) dominance of sicklepod (*Senna obtusifolia*) on river benches.

Introduced perennial pasture grasses such as Indian blue grass (*Bothriochloa pertusa*), sabi grass (*Urochloa mosambicensis*) and many others generally have variable influences on the overall hydrological balance of river frontage soils above alluvial gully zones, compared to native grasses. The stoloniferous nodes and advantageous spreading of these sod forming species promote good soil cover and rooting strength, and are used for erosion control for many purposes (e.g., Sections 7.6.2 and 7.13). The root biomass of these stoloniferous species is moderate compared to other species (Section 7.13.5; Figure 116); however the root biomass and above ground biomass of tufted perennial grasses can be higher (native and exotic). Water infiltration rates into the soil can be slightly higher for these stoloniferous grasses compared to tufted native perennials – all other factors being equal – as seen in experimental results in this report (Section 7.13.5; Figure 122).

Scanlan et al. (1996) document *lower* water runoff volumes during rainstorms from exotic *Bothriochloa pertusa* grasslands compared to native *Heteropogon contortus* grasslands under similar cover conditions. He hypothesised that the more even distribution of cover and roots of the stoloniferous *Bothriochloa pertusa* had a greater reduction in velocity and water detention compared to native tussocks, promoting infiltration and evaporation. Scanlan et al. (1996) emphasised however that good perennial grass cover, exotic or native, was most beneficial to reducing surface erosion and water runoff, regardless of exact species' traits.

The influence of purposefully introduced pasture legumes and shrubs (Miller et al. 1988) on the soil hydrological cycle of river frontage floodplains and terraces upslope from river banks and alluvial gullies remains less clear. Introduced legumes (*Stylosanthes spp.*) have been documented to have both positive and negative consequences for native pasture production. Negative consequences include soil acidification, nutrient depletion, changes in native species' dominance, and increased soil erosion (Noble et al. 2000). Species such as shrubby stylo (*Stylosanthes scabra*) likely have benign or positive influences on pasture hydrological cycles, as they generally do not compete aggressively with native grasses, can infill gaps between grass tussocks, can fix nitrogen, and have decent root biomass (Section 7.13.5; Figure 116). In contrast, other aggressive pasture legumes like Caribbean stylo (*Stylosanthes hamata*) and wynn cassia (*Chamaecrista rotundifolia*) tend to out compete and smother native grasses over time (Noble et al. 2000; O'Gara 2005). In seasonally dry climates on Cape York Peninsula, wynn cassia tends to behave like an annual and desiccate toward the end of the dry season. This produces a decent layer of leaf and stem mulch covering the ground surface, but the lack of perennially attached plant parts and low root biomass (Section 7.13.5; Figure 116) provide little in terms of root cohesion and roughness protection from overland runoff. Wynn cassia tends to not grow well in gullies due to nutrient-poor, hard-setting, sodic soils, and would be generally ineffective at perennially stabilizing gully soils with good root structure and cohesion (Section 7.13.5; Figure 116).

The widespread invasion of sicklepod (*Senna obtusifolia*) onto river benches and inset floodplains has had an unknown effect on alluvial gully initiation and acceleration. Sicklepod invaded open areas of river banks that were previously occupied by native herbs and shrubs and grassland pockets of blady grass (*Imperata cylindrica*), kangaroo grass (*Themeda triandra*), and other native grasses. The extent that this destabilised river benches and initiated head-cutting up hollows and gullies is unknown. Regardless, the control of sicklepod is a major challenge regionally (Mackey et al. 1997; QDEEDI 2011b). Herbicide spraying and burning are fairly ineffective over large scales, plus it has a long seed life, but some advances in biological control remain promising (Mackey et al. 1997; Palmer 2012).

The impacts of rubber vine (*Cryptostegia grandiflora*) on gully erosion in riparian zones also remain unquantified. Dense thickets of rubber vine can effectively shade out understorey grasses along steep banks and river benches, leaving alluvial soils bare underneath. This can change the resistance to erosion along steep banks and hollows, making them more vulnerable to gully erosion (Shellberg 2011). Intense 'storm burns' in the early-wet season after initial heavy rain (>25 mm in 24 hrs) can be used to control rubber vine along river frontages, but the impacts of these intense fires on ground cover and short-term soil and gully erosion remain a major concern (Section 6.5.7).

On most cattle stations, weeds are spread through multiple mechanisms including 1) cattle and their dung, 2) station vehicles and machines along roads, tracks and fences, 3) the transport and use of imported hay for supplemental feed, 4) direct sowing of introduced pasture species, 5) exotic and native animals such as pigs and wallabies, 6) rivers during flood, and 7) fire and wind. Eliminating or reducing the spread of weeds through these pathways remains one of the biggest challenges for pastoral properties in northern Australia.

Chemical controls of weeds using herbicides can be effective at controlling weeds especially in their emergent state before seeds are set (e.g., Mackey et al. 1997; Volger 2009), but typically only over small areas or in open cleared paddocks or along roads, tracks and fences. Herbicide use over large areas and long lengths of river frontage can be cost prohibitive. Furthermore, herbicide use in complex riparian zones is challenging and could have negative impacts on water quality if done incorrectly (Howley et al. 2013). Mechanical control of weeds (e.g., cutting, disking, ploughing) can also be effective, but requires either high manual labour inputs or use of machinery on already cleared land. Mechanical control by hand is only appropriate for some species along riparian zones (e.g., rubber vine, QDEEDI 2011), while larger scale machine mechanical treatments along un-cleared river frontages could promote soil disturbance and erosion. Biological control of weeds has been modestly successful in Australia (e.g., rubber vine rust, QDEEDI 2011a). While a panacea in some cases, biological controls remain promising for some of the worst invasive species (e.g., sicklepod, Mackey et al. 1997; Palmer 2012).

Over large scales, the combined and rotated use of fire and wet season spelling of cattle are the best tools to promote the health, vigour and competitiveness of native perennial grass, along with the suppression of weed growth and expansion. This is especially true along river frontage zones of pastoral properties where disturbance tends to be highest creating weed invasion and competition opportunities. Wet season spelling of river frontage paddocks is critical for promoting natural cycles of perennial grass growth and reproduction through tillering and seeding (Section 6.5.2; Rolfe et al. 2004; O'Reagain et al. 2011). However when rotating cattle between paddocks, extreme caution is needed to not spread weed seeds consumed by cattle. Thus quarantine and holding paddocks need to be managed well and kept weed free during and after transitions (Darryl Paradise, Kings Plain, personal communication). Both early-dry season and early-wet season fires could be effective at weed control and nurturing cycles of native grass production (Section 6.5.7; Crowley and Trueman 2005; Reef Catchments 2011). However, the exact timing of fires needs to be carefully balanced with the different seed cycles of both native and exotic species, available soil moisture and fuel loads, and the ability to burn at the desired time to reduce weed seed production. In some cases, fire at inappropriate times can spread weed species (e.g., grader grass, Keir and Volger 2006; Volger 2009). More field research is a major priority to quantify these weed control variables along river frontage in relation to reducing water runoff and gully erosion.

In areas where weed invasion has permanently changed river frontage and riparian areas, restoration of the full suite of native species might not be possible and alternative states of ecosystem, species and soil equilibrium will need to be found that promote soil conservation, biodiversity and local economies to the greatest extent possible.

6.5.9 Road and Fence Placement, Construction, and Maintenance on River Frontage with Dispersive or Sodic Soils

The construction of roads and fences through erodible alluvial soils along river frontage will invariably cause accelerated erosion. Improper placement, construction, and maintenance of dirt roads and tracks can concentrate water runoff and accelerate local and off-site gully erosion (Pressland et al. 1988; Hadden 1993; Jolley 2009). This is especially true on dispersive or sodic soils along river frontage terraces and high banks on Cape York Peninsula, such as in the upper Normanby catchment (AGSO 1995; Brooks et al. 2013). Most often this erosion is concentrated on the banks of hollows, creeks, and river crossings, where soil disturbance and/or grading with machines without water diversion structures leads to deep gully erosion and eventual road abandonment. Building roads through dispersive or sodic soils on terraces and elevated floodplains should be avoided.

The best long-term solution to road and fence stability is to locate this infrastructure away from dispersive or sodic soils along river frontage, and not following the easiest or straightest path up the river valley or slope. The preferred location of roads and tracks is stable soils and geology, such as on subtle ridge and spur crests between drainage catchments. Carefully planning road and fence routes will minimise the number of crossings of existing gullies, unchannelled hollows, creeks, and rivers. This will reduce maintenance costs and minimise the potential for rill and gully erosion often created at steep banks at water crossings. Where roads are needed across sodic soils, the road path should follow shallow ridges along terraces, which divide subtle catchments that drain toward river banks where alluvial gullies usually initiate. Satellite images (Google Earth), basic soil/geology and erosion hazard maps, topographic maps, and LiDAR topographic data can be used to identify the most appropriate locations for roads, subtle but important catchment divides, and potential crossings of hollows, gullies, creeks, and rivers to avoid. Distribution maps of alluvial gullies and erosion hazards (AGSO 1995; Brooks et al. 2006; 2009; 2013) can be used to avoid problem areas altogether. Once preliminary routes are identified, field reconnaissance and route mapping using motor bikes, GPS, topographic maps and Google Earth images should be used to more precisely locate erosion hazards and adjust road locations accordingly.

Grading or bulldozing down steep banks at water crossings to provide road access will most often initiate and accelerate alluvial gully erosion. Continuous cutting of these slopes with machines without installation of BMP structures leads to chronic erosion and the eventual need for road abandonment, initiating vicious erosion cycles (see Section 7.14). Where water crossings are needed across steep banks of sodic alluvium, topographic irregularities in the banks should be sought to locate the road down the gentlest slopes. Road cutting should be kept to a minimum, and preferentially machines would only be used to place BMP structures and imported rock on top of the native soil surface for improved drainage. Vegetation clearing should also be minimised on steep banks. Road crossings should be angled upstream on both approaches to reduce the concentration of water flow into the valley. On steep slopes in erodible soils, frequent water diversion banks (i.e., large ‘whoa boys’) should be placed down the road slope every 10-15 metres (Table 7) to check water flow and reduce sheet, rill, and gully erosion. To protect exposed sodic soils from enhanced erosion and to extend the crossing longevity, road approaches on steep slopes should be armoured with suitable coarse angular rock borrowed from either local bedrock pits, or if necessary from gravel in nearby creeks or rivers (see Section 7.14).

Annual machine grading of tracks and roads on fairly flat slopes can also lead to entrenchment of the road into the landscape and concentration of water flow, unless frequent water diversion banks (whoa boys) are installed and grading is both light and skilful to maintain road and BMP integrity. Thus, even low gradient road surfaces on alluvial terraces and floodplains need frequent water diversion structures, as heavy rainfall on low permeability sodic soils can lead to abundant water flow down roads on gentle slopes (Section 7.14). Maintaining or reinstating natural water flow paths is essential for erosion control on roads. Time and allocated budgets are needed to maintain frequent water diversion structures on roads to ensure that rill and gully erosion do not accelerate out of control due to negligence. Repairing severely degraded roads to maintain access and reduce gully erosion is very costly and difficult. Thus is reviewed in Section 7.14.

7 Rehabilitation of Alluvial Gullies

7.1 Rehabilitation and Restoration Philosophies

Humans often intervene in natural or human accelerated processes such as gully erosion or river instability in attempts to engineer stability, promote human uses of the environment, or repair environmental damage caused by humans. Often these interventions focus on 'technological fixes' and engineering that aim to fix or repair or improve natural processes degraded by human actions (Katz 2000). This anthropocentric world view often creates landscape 'artefacts' for human needs, but often falls short of truly restoring natural processes (Simon et al. 2007) and can be akin to 'faking nature' (Elliot 1982).

The extent that natural processes can actually be restored back to the pre-disturbance conditions often depends on the extent of initial degradation (Roni et al. 2005). For the least disturbed situations, a case can be made for preservation or limitation of further degradation (see Section 6 on Prevention of Alluvial Gully Initiation on Grazing Land). For more degraded conditions, a case can be made for restoration, rehabilitation, mitigation, or in extreme cases, dereliction (Boon 1992). In rangeland grazing situations, Saar (2002) reviewed several degradation and recovery pathways once livestock were excluded from a given area (Figure 32). Depending on the severity of the degradation and the nature of the forms and processes involved, recovery could return towards the pre-existing state fairly quickly (Figure 32a; rubber band model), never recover to the pre-existing state (Figure 32b; the humpty dumpty model), or return to a pre-existing state after a long recovery period (Figure 32c; the broken leg model).

Alternatively for geomorphic degradation and recovery in fluvial situations such as degraded rivers or incising gully channels, Brierley and Fryirs (2005) highlight the several different recovery pathways or restoration trajectories that can occur due to natural recovery or human management intervention (Figure 32d). If the degradation pathway is not too severe, then restoration actions can bring the geomorphic conditions and processes back toward, but not completely to, the intact pre-disturbance condition. However if geomorphic turning points are passed along the degradation pathway, then intervention actions will not result in restoration, but rather in the creation of a new condition that falls between the fully restored and fully degraded scenarios (Figure 32d). This is most often the case in river rehabilitation.

Systematically there is inadequate monitoring to assess the degree of success of rehabilitation or restoration efforts (Bernhardt et al. 2005; Fryirs et al. 2013), let alone recovery trajectories. Often the existing condition, degradation pathway, recovery potential, and restored condition goal are poorly defined. More recent riverine and landscape restoration paradigms have focused on learning from history (Wohl et al. 2005; Wohl and Merritts 2007; Kondolf et al. 2006; Mika et al. 2010) and working with and promoting natural recovery processes to the greatest extent possible at both the local and landscape scales (Brookes and Shields 1996; Ebersole et al. 1997; Thexton 1999; Callahan 2001; Simon et al. 2007).

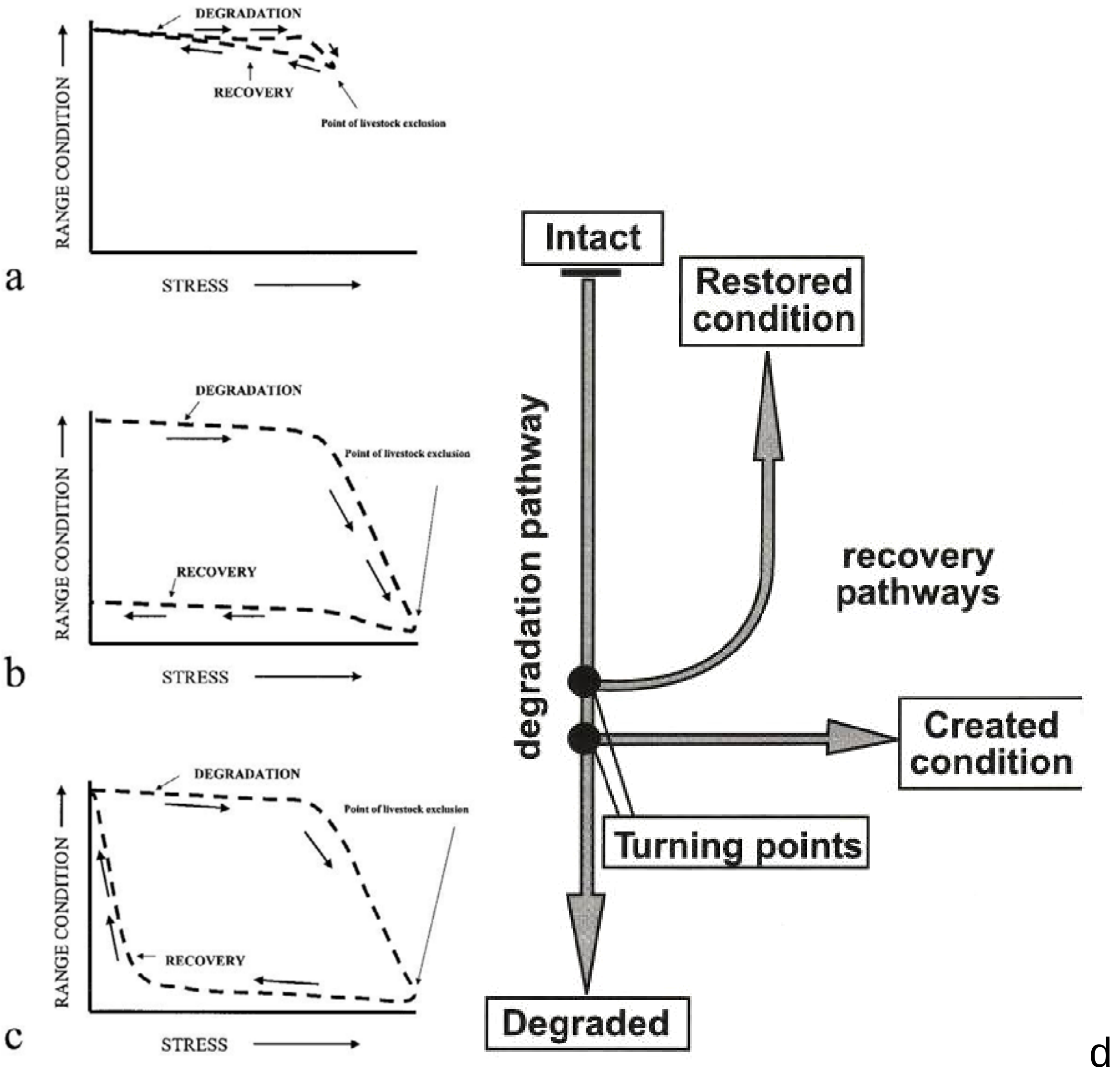


Figure 32 Different degradation and recovery pathways following different stress and rangeland conditions including a) the rubber band model, b) the humpty dumpty model, c) the broken leg model (from Saar 2002), and d) turning points along a degradation pathway where land management intervention could recover restored or created conditions (from Brierley and Fryirs 2005).

7.2 Cumulative Effects, Rehabilitation Potential, and Gully Erosion

7.2.1 Definitions

Often the impacts of environmental degradation are not caused by a single action, location and/or source. More often environmental change is caused by the cumulative sum of individual actions, locations and/or sources across space and time.

- ***Cumulative effect*** can be defined as "*any environmental change influenced by a combination of land-use activities.*" (Reid 1993).
- ***Cumulative impact*** can be defined as "*the impact on the environment which results from the incremental impact of the actions when added to other past, present, and reasonably foreseeable future actions regardless of what agency or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time.*" (CEQ 1971).
- **Cumulative watershed effects** (CWE) can be defined as "*off-site, downstream changes in hydrology, sediment production, transport, and temporary storage in response to land management practices within a drainage basin*." (Swanson 1986).

Across time and space, cumulative effects can be either additive or synergistic. With synergistic effects, cumulative effects can be greater than the sum of their individual effects. "*Cumulative effects can be caused by repeated, progressive, sequential, and coexisting land-use activities*" (Reid 1993). Different land use activities (e.g., grazing, mining, logging, agriculture, urbanization) can have a 1) single type of influence (e.g., cattle tracks concentrating water runoff), 2) complementary influences (e.g., cattle tracks and grazing down grass cover both accelerate water runoff), 3) cascading influences (e.g., cattle spreading weeds brought into an area by the mining industry), and 4) interdependent influences (e.g., both mining and grazing incremental development create the need for a new bitumen highway) (Reid 1993).

Impacts at a given site or catchment can be cumulative over time, such as with cattle walking along and cutting down the same cattle track (pad) over decades, or roads being graded down incrementally year after year for decades eventually creating large gullies. Impacts can be cumulative over space, such as with the incremental and semi-permanent increase in road or fence density that cumulatively increase water and sediment runoff at the catchment scale. Alternatively, spatial cumulative impacts can occur from the widespread grazing of cattle that can reduce grass cover at the catchment scale, increase water and sediment runoff, and create cascading influences on altered fire regimes and the spread of weeds.

The actual environmental change causing cumulative effects can be diverse and variable, for example, changes in vegetation cover condition, soil condition, erosion extent and magnitude, water pollution, road building and maintenance, and urban impervious surfaces. Cumulative watershed effects have been well documented as a result of grazing (e.g., Grider 1995), road networks (e.g., Cederholm et al. 1981; Reid 1993; 1998; Short 2013), agriculture (Jang 2013), logging (e.g., Cederholm et al. 1981; Reid 1993; 1998), mining (e.g., Lucas et al. 2009), and urbanization (e.g., Hammer 1972). For pollution of waterways with excess sediment, nutrients or chemicals, pollution sources can either be from '*point sources*' from discrete locations (industry pipe outfalls, agricultural ditches) or '*non-point sources*' that enter waters from any dispersed land-based or water-based activities. Excess sediment and nutrient runoff from grazing, forestry, agriculture and roads is typically classed as non-point source pollution, although processes such as road and gully erosion in some cases can be more akin to point sources.

Legislation and management in Australia has failed to address the cumulative effects issues when assessing, managing or planning land use or development activities at the catchment scale to minimise impacts to the environment (e.g., EPBCA; Dales 2011). Therefore, many seemingly insignificant individual actions or events are left unmanaged or regulated at State or Federal levels, while their cumulative effects are having major impacts at the catchment scale. This is the case, for example, when the actions at one grazing property or mining site in a catchment are having modest impacts, while the actions of multiple properties or mines over a given area are cumulatively having major impacts on downstream water bodies. More recently, however, a few cumulative impacts assessments have been conducted in Australia associated with the mining boom, where the combined impacts of multiple large mines are having significant cumulative effects (Lucas et al. 2009). In other countries such as the United States, cumulative effects are legally taken into account at Federal and State levels when assessing the impacts of land use activities on ecosystems, species, and waterways (CEQ 1971; Reid 1993; Reid 1998; USEPA 1999; Dales 2011; Short 2013).

Quantifying and documenting cumulative effects at the catchment scale remain problematic due to the intensive monitoring needs over long time scales and the scale effects (Reid 1993; Reid 1998; Bunte and MacDonald 1999). Most often the detection of cumulative watershed effects is obtained by monitoring water, sediment and water quality conditions before and after land use change in both treatment and control catchments, typically over a minimum period of 10-20 years. Cumulative effects appear to be most detectable in catchments 50-500 km^2 in area (Bunte and MacDonald 1999). Detecting changes at larger scales is problematic due to dilution and scale effects, unless the entire large catchment is under significant land use change (widespread grazing, agriculture, urbanization, forestry etc.). In addition, detecting sediment cumulative effects should not be expected until there is at least a doubling in sediment yield, due to the inherent error in measuring and monitoring sediment yield over time (Bunte and MacDonald 1999). Unfortunately due to the effects of time lags and internal sediment stores, by the time you can categorically measure a doubling in sediment yield at the outlet of a large catchment, permanent damage will have been done, as many internal thresholds will likely have been crossed (e.g., extensive gully erosion initiated).

7.2.2 Rehabilitation Through Cumulative Actions

Rehabilitation or restoration of a landscape affected by cumulative land use impacts requires cumulative actions at the catchment scale to remedy the situation. The incremental degradation of a catchment site-by-site over one-hundred years could imply that rehabilitation actions will be needed site-by-site over the next one-hundred years. Small site specific rehabilitation actions (e.g., stabilizing gullies along a degraded road) will likely have only modest and small incremental changes on the overall catchment situation (e.g., sediment load). Even where hundreds of millions of dollars are invested in thousands of projects through major restoration programs, the degree that these efforts are successful depends on the magnitude of the historical land use changes (e.g., Kondolf et al. 2008). Restoration of the Normanby catchment for example would be cheaper and more practical than the more developed and degraded Burdekin catchment, but both would require incrementally addressing cumulative effects. However, modest changes at the catchment scale in degraded catchments are still important to reverse the trend in degradation and in some cases this may be enough to enhance the survival or integrity of endangered species or ecosystems (Kondolf et al. 2008).

Prioritizing catchment rehabilitation efforts can ensure that the most influential and cost-effective projects are conducted first. Unfortunately, the easiest and cheapest projects are often done first in practice due to economic constraints and social values, but this does not ensure they are the most effective for environmental outcomes (Kondolf et al. 2008). More appropriately, systematic field reconnaissance surveys can be used to assess the magnitude and risk of sediment delivery, and then use these ranks for prioritizing and targeting the most effective sites for action (e.g., road erosion, Takken et al. 2008). In more complex catchment assessments, sediment budgets can be used to prioritise concentrated areas of erosion that are priorities for sediment reduction action (e.g., Brooks et al. 2013).

Numerous modelling efforts have been developed to prioritise incremental and cumulative sediment reduction efforts (e.g., Lu et al. 2004; Jang et al. 2013). Often catchments are broken down into subunits and erosion processes, and these are then ranked according to their marginal change in sediment load per conservation dollar invested (Jang et al. 2013). However in order for the rehabilitation prioritization to be truly effective on the ground in nature, the scientific models, analyses, and underlying assumptions need to be correct. For example, in the Normanby catchment, previous modelling and prioritization efforts to reduce fine sediment loads suggested targeting hillslope erosion, but subsequent field work, sediment tracing and modelling demonstrated that bank and gully erosion were the priority areas for rehabilitation efforts (Brooks et al. 2013). Similar issues could arise over trying to prioritise bank erosion vs. gully erosion priorities.

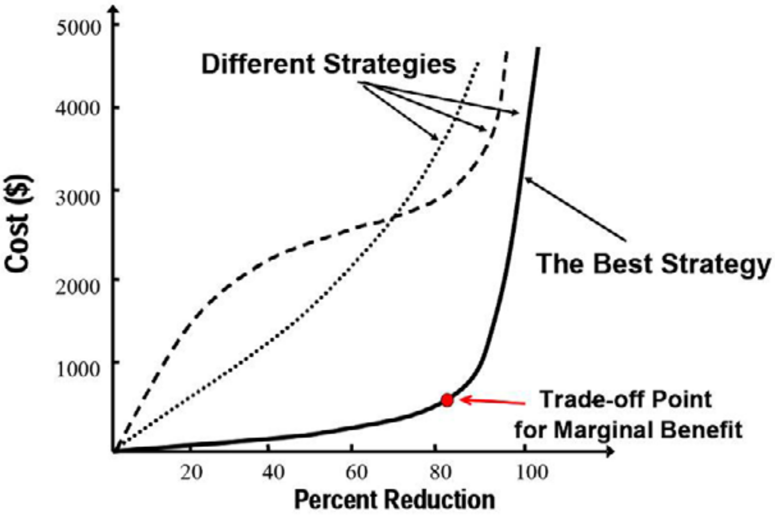


Figure 33 Conceptual diagram for the economic optimization of cost-effective sediment reduction (from Lu et al. 2003).

Unfortunately, prioritization still does not solve the need for cumulative rehabilitation actions to address cumulative effects. For example in the Normanby catchment, Brooks et al. (2012) used field reconnaissance, satellite and LiDAR mapping and sediment tracing to determine that (via tracing) 87% of the fine sediment was originating from sub-surface sources, while (via budgeting) 37% originated from gully erosion and 54% from bank erosion along small channels (Figure 16). Maps of alluvial and colluvial gully erosion (Figure 15; Figure 14), indicate that these gullies are widely distributed across the catchment, but often concentrated in areas that are highly prone to erosion (e.g., floodplain margins, footslopes of hillslopes). Since alluvial gullies are a major sediment source and often concentrated in specific areas, it is logical to target these as priority areas for rehabilitation action (e.g., the Granite Normanby River). However, once one focuses into these concentrated areas of erosion on the ground, it is quickly realised that the problem is still a cumulative effects issue, where literally thousands of alluvial gullies covering thousands of hectares exist within one concentrated area.

7.2.3 Cumulatively Addressing Gully Erosion in the Normanby Catchment

Human accelerated alluvial gully erosion in northern Australia due to cattle grazing and associated European land use practices is a classic cumulative effects problem. For example in the Normanby catchment, the roughly 37% of fine sediment originating from gully erosion in the catchment comes from tens of thousands of gullies (Figure 14; Figure 130; Brooks et al. 2013). Most but not all of these gullies have likely been influenced by the impacts of ubiquitous cattle grazing (i.e., grass cover reduction, increased water runoff, cutting cattle tracks, weed spread, etc.) over the last 130 years (Figure 8; Figure 9; Shellberg et al. 2010; Shellberg 2011; Brooks et al. 2013). While many of these gullies are concentrated in erosion prone areas at the sub-catchment scale, those areas contain thousands of individual gullies that cumulatively elevate sediment loads (Figure 14; Figure 130).

Cumulatively reducing soil erosion from these gullies will take many incremental cumulative actions over decades. Different strategies for reducing gully erosion at the catchment scale will be needed. Around key areas of human interest such as roads, fences, yards, dams, improved paddocks and indigenous cultural sites, direct/intensive intervention using bioengineering approaches (structure and vegetation) to stabilise gullies will be appropriate and needed (Sections 7.6 to 7.13). These efforts will be costly initially, but long-term gains will be made by ensuring stable infrastructure and minimal long-term maintenance or ongoing damage. In more remote grazing lands where infrastructure is not threatened, use of direct/intensive intervention will only be warranted when key natural resources are threatened (e.g., unique lagoons, key ecosystems) or when large gullies are at the initial stages of the evolution and could be stopped before consuming large areas of land and soil. In the latter case there is a cost/benefit ratio of the amount of soil area that can be prevented from eroding and the cost of protecting it. In remote areas, direct aerial seeding of grass seeds could also be warranted if large gains are made in stabilizing gullies across large areas.

In most other cases in remote grazing land, large-scale indirect/passive rehabilitation approaches will be needed to reduce existing and future gully erosion (Sections 6 and 7.5). These include permanent destocking of cattle, wet season spelling of cattle, intensive rotational grazing with bursts of grazing and long rest periods, indirect/passive revegetation of grass vegetation, altered or abandoned road and fence use, and a return to a mosaic (patchy) fire regime that reduces intense late-dry season fires through river frontage.

The success of these large-scale indirect/passive measures will need to be monitored scientifically over long time scales to detect the slow and incremental changes from removing or changing stressors to the ecosystem (i.e., cattle, fire, weeds). Lessons learned from other indirect/passive restoration experiments across Australian grazing lands will also be useful in guiding management scenarios (e.g., stocking rates and spelling regimes) and the practicalities of restoring extremely degraded rangelands (e.g., O'Reagain and Bushell 2011 in the Burdekin catchment; Ciesiolka 1987 and Silburn et al. 2011 in the Fitzroy catchment, Qld, Figure 34).

Preventing gully erosion from occurring in the first place is far cheaper and easier than direct/intensive or indirect/passive rehabilitation efforts. Cattle and land management actions that reduce or prevent gully initiation should be implemented as a high priority, such as excluding stock from steep river banks and river frontage zones with dispersive or sodic soils using fencing and off-stream water points. Unfortunately in many of the potential areas prone to gully erosion in the Normanby catchment or beyond, gully erosion has already been triggered by historic land use (overgrazing, roads, fences fire, weeds). Thus, future prevention through active cattle and road/fence management will help, but cumulative rehabilitation will still be needed at thousands of sites already initiated.

7.3 Gully Rehabilitation Scientific Literature and Practical Manuals

For gully erosion, a wide range of physical, biological, and chemical techniques are used to modify both gully form and processes to meet varying objectives of natural resource management. To date, there have been relatively few attempts to synthesise the full range of scientific research and on-ground techniques used to reduce or rehabilitate gully erosion around the world. This is in contrast to the more detailed progress of stream and river restoration science and application (e.g., Brookes and Shields 1996; Rutherfurd et al. 2000) and the broader research field of incising channels (e.g., Wang et al. 1997; Darby and Simon 1999). However in sum there is a large body of literature and experience directly and indirectly applicable to gully rehabilitation that draws from the fields of hydrology, geomorphology, soil science, agricultural, rangeland science, ecology, geotechnical engineering, bioengineering, and watershed management.

7.3.1 Scientific Literature on Gully Control and Rehabilitation

Scientific reviews of gully control and rehabilitation have been few, but with several notable exceptions (e.g., Heede 1978; Haigh 1984; 1998; Boucher 1990; Lal 1992; Grissinger 1996). However, the number of international science papers reviewing the success and failure of gully prevention and control projects has been increasing over the last few decades for 1*) grade control structures* (e.g., Barnhardt 1989; Gellis et al. 1995; Marston and Dolan 1999; Norton et al. 2002; Weinhold 2007; Shields et al. 2007; Castillo et al. 2007; Wilson et al. 2008; Boix-Fayos et al. 2008), 2) *using vegetation for gully control* (e.g., Reubens et al. 2009; Molina et al. 2009) and 3) *restoring vegetation on hillslopes above gullies* (e.g., Law and Hansen 2004; Chen and Cai 2006; Marden et al. 2011).

The reoccurring '*International Symposium on Gully Erosion*' has held six conferences over the last decade on the process-based science surrounding gully erosion and its control [Belgium (Poesen and Valentin 2003); China (Valentin et al. 2005); USA (Romkins and Bennett 2005); Spain (Casali et al. 2009); Poland (Janicki et al. 2011); and Romania (Ionita 2013). However, the focus on gully rehabilitation at these conferences is typically a small component (Poesen 2011).

In Australia, most of the scientific knowledge surrounding gully prevention, stabilisation, and rehabilitation is contained within the '*Journal of the Soil Conservation Service of New South Wales*' between 1945 and 1988. This journal is not readily available to people outside Australia. Geographically, research in this journal was focused on New South Wales, Victoria and central Australia, with very few articles focused on tropical northern Australia or gully erosion into sodic soils of terraces and elevated floodplains. However there is a wealth of scientific and practical knowledge on topics such as pasture degradation (e.g., Condon et al. 1969), erodible duplex soils (e.g., Alchin 1983), scald reclamation (e.g., Jones 1969; Cunningham 1974; Muirhead et al. 1974; Quilty 1986), tunnel erosion (e.g., Floyd 1974), gully control (e.g., Quilty 1973a; Young 1973; Starr 1977; Stannard 1977; Crouch et al. 1984), contour structures (e.g., Quilty 1972a; 1972b; 1972c), and earthworks (e.g., Quilty 1973b; Wickham 1976; Elliott 1979; 1980), among many others. Much of this research and field implementation of soil conservation measures was funded and conducted by Soil Conservation Service staff and scientists working with landowners directly on the ground. This type of hands-on field research, implementation trials, and long-term government programs for soil conservation faded after the 1980's, and was not widely extended to remote areas of northern Queensland. A strong argument could be made to recreate this type of management/science partnership in northern Australia.

7.3.2 Practical Manuals and Grey-Literature on Gully Control and Rehabilitation

Much of the knowledge on gully control is held within practical manuals for gully stabilization using (bio)engineering techniques (e.g., Heede 1976; Geyik 1986; Bartlett 1991; Gray and Sotir 1996; NRCS 2007b). Some of these will be reviewed below for Australia.

In Australia, the most notable manual for major earthwork intervention for numerous soil conservation purposes is the '*Earthmovers Training Course*' developed by the Soil Conservation Service of New South Wales (Bartlett 1991; Table 3). Much of the detail in this manual came from scientific research in the '*Journal of the Soil Conservation Service of New South Wales*' and practical field experience moving earth for soil conservation purposes. The manual focuses on the use of heavy machinery (graders, bulldozers, tractors, excavators, etc.), for soil conservation and erosion control purposes. It relies on an engineering paradigm and 'technological fixes' that aim to fix, repair or improve natural processes degraded by human actions. These engineering interventions might or might not actually reduce soil erosion. The manual minimally addresses soil erosion processes, causes of erosion, geomorphology, and channel evolution, but does cover basics on soil science and water runoff calculations needed to understand erosion potential. There are several key chapters that are applicable to gully erosion stabilisation (Table 3), but especially the chapter on 'Gully Filling and Shaping' (Mullavey 1991).

Table 3 Units applicable to gully erosion control from the 'Earthmovers Training Course' developed by the Soil Conservation Service of New South Wales (Bartlett 1991).

Unit #	Title	Author
4	Erosion Control & Design Principles	Jackson 1991
9	Farm Dams	Greentree and Jackson 1991a
10	Construction of Farm Dams	Greentree and Jackson 1991b
11	Contour & Graded Banks	Jackson et al. 1991
12	Construction of Banks	Greentree and Pinkerton 1991
13	Waterways	Pinkerton and Jackson 1991
14	Construction of waterways	Pinkerton and Greentree 1991
15	Gully Filling and Shaping	Mullavey 1991
17	Access Tracks	Marshall and Norvill 1991
19	Flumes and chutes	Adams and Mitchell 1991

In Queensland, there are several complementary design manuals for soil conservation measures developed by the Queensland Government (QDERM 2004a), with chapters on contour banks (QDERM 2004b) and engineered waterways (QDERM 2004c). Queensland soil conservation scientists also have reviewed many NSW gully control and drop structures for use in Queensland (Crothers et al. 1990). Most recently, Queensland soil conservation scientists have created a series of (draft) Fact Sheets related to gully erosion, soil erodibility, sodicity, dispersion and slaking (Table 4). These valuable summaries should be available to the public soon on http://www.nrm.qld.gov.au/land/management/erosion/. The fact sheets on soil erodibility, sodicity, dispersion and slaking are very applicable to sodic soils where alluvial gullies initiate on terrace and floodplain margins in northern Australia. However, much of the review on gully development, prevention and control is focused on colluvial or hillslope gullies in southeast Queensland, rather than alluvial or floodplain gullies in northern Queensland.

Several recent 'e-books' have been developed by Bruce Carey (Queensland soil conservation scientist) on dispersive soils (Carey 2012a) and the history of soil conservation in Queensland (Carey 2012b). The former focused on the history of soil conservation measures implemented on cleared agricultural land in southeast and central Queensland.

Table 4 Draft 'Fact Sheets' created by Queensland Government, available soon at: http://www.nrm.qld.gov.au/land/management/erosion/.

Fact Sheet Title	Author
Gully erosion – An introduction	Carey 2013 (draft)
Gully erosion – How gullies develop	Carey 2013 (draft)
Gully erosion – Prevention and control	Carey 2013 (draft)
Gully erosion – Bed stabilisation measures	Carey 2013 (draft)
Gully erosion – Bed stabilisation measures design	Carey 2013 (draft)
Soil erodibility	Carey 2013 (draft)
Sodicity and water quality	Carey 2013 (draft)
Soil dispersion - Management	Carey 2013 (draft)
Soil dispersion and slaking - Identification	Carey 2013 (draft)
Soil dispersion and slaking	Carey 2013 (draft)

A large body of grey-literature has been produced by Australian governmental agencies and field-practitioners in order to synthesise the knowledge and complexity of gully erosion control. This literature covers - in various forms - the evolving state-of-the-art of gully stabilisation and BMPs for predominantly hillslope/colluvial gullies (Milton 1971; Condon 1986; 1988; Crothers et al. 1990; Bartlett 1991; Hadden 1993; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008; Miller 2008; Jolley 2009; Alt et al. 2009). These BMP manuals targeted a mixed audience of laymen, landowners, managers, equipment operators, natural resource monument officers, government bureaucrats, consultants, and scientists. Only a few of these partially address the more unique situation of alluvial gullies in northern Australia (e.g., Condon 1986; 1988; Hadden 1993; Jolley 2009). There is much to learn from this suite of knowledge and experience; however a lack of rigorous documentation and scientific data for these gully stabilisation examples, techniques, and guidelines reduces information accessibility and assessment. Most techniques outlined in these BMP manuals rely on heavy engineering intervention with gullies, without enough consideration of original causes of gully initiation, geomorphic processes, stage of intervention during gully evolution, use of vegetation to promote long-term stability, and major changes in land use practice to prevent future gullying. Some of these gully engineering practices are successful in reducing erosion and sediment yield. However, many result in failure due to poor implementation and lack of integration of process-based scientific knowledge. Few are monitored or maintained over time due to a ‘set and forget’ paradigm. Overall, the practice of gully erosion control lacks field monitoring, adaptive management, and documentation of results to improve knowledge and success into the future.

7.3.3 Gully Erosion Control Manuals for Grazing Land in Northern Australia

Specific manuals for gully erosion control on grazing land in northern Australia are limited in extent. In the Northern Territory, Jolley (2009) focused on erosion control on cattle station roads and fences, in addition to rehabilitating degraded open savanna plains using a variety of disk, pitter, and furrow ploughs and reseeding. Gully erosion prevention is addressed for road and fence situations, where water runoff is best managed with frequent diversion structures. However, addressing and rehabilitating existing gullies was deemed to have no economic return (Sullivan and Kraatz 2001), but downstream environmental and cultural costs were not considered. These road and fence BMP guidelines have formed the basis of many workshops held around northern Australia (e.g., NTAA 2010), mainly focusing on training graziers and equipment operators how to install basic water diversion structures along roads and fences.

7.3.4 Sodic Soil Management

Sodic soils (Sodosols) cover greater than 25% of Queensland and are highly prone to gully erosion (Shaw et al. 1995; Naidu et al. 1995). Because sodic soils are a major management concern for agriculture production, grazing, erosion, and downstream sedimentation of waterways, considerable scientific research has been published and numerous management reviews have been developed to guide land managers. Much of the science on sodic soils in Australia is reviewed in Naidu et al. (1995), in addition to scientific reviews on reclaiming sodic soils (e.g., Keren 1996; Suarez 2001). Management guidelines for sodic soils have been published by Hardie et al. (2009), but for a different climate zone. In Queensland, Carey (2012a) produced a recent e-book on dispersive soils and soil erosion. Boucher (1990; 1995) reviewed management options for sodic soils that are affected by tunnel and gully erosion. This wealth of knowledge is very relevant to the management of sodic soils affected by alluvial gully erosion along terraces and elevated floodplains of river frontage in northern Australia.

7.3.5 Summary of Relevance to Alluvial Gullies in Northern Australia

Learning how to prevent, stabilise, and rehabilitate alluvial gullies in northern Australia will take considerable efforts in practical field experimentation, science monitoring, adaptive management through lessons learned, cumulative efforts at the catchment scale to reduce gully erosion, and considerable economic and social analysis of how to make that happen. It is clear that directly importing management approaches from hillslope/colluvial gullies in southern Australia is unlikely to provide a solution to managing alluvial/floodplain gullies in northern Australia, although there is much that can be learnt from past successful and unsuccessful experiences within Australian and globally.

In each section throughout the remainder of this report, the existing scientific and grey literature on gully rehabilitation will be reviewed for the relevant topic.

7.4 Principles of Gully Erosion Control

From the scientific and grey literature reviews above, there are three main approaches to reduce gully erosion once started, which generally should be used in combination (Heede 1976; Lal 1992; Haigh 1984; Thorburn and Wilkinson 2013). These will be reviewed throughout Section 7.

1. Reduce water runoff into and through gullies.
2. Stabilise gully headcuts and sidewalls with vegetation and/or physical structure.
3. Reduce the gully channel slope and increase roughness using grade control structures and/or vegetation, which will trap sediment and promote revegetation.

7.5 Indirect/Passive Revegetation Through Natural Recovery and Resilience

7.5.1 Literature Review

Once gully erosion has initiated, gullies typically erode along an evolutionary cycle until an equilibrium slope and form is reached (Schumm and Hadley 1957; Schumm 1973; Graf 1977; 1979; Rutherfurd et al. 1997; Brooks et al. 2009; Shellberg 2011). Vegetation can play an important mitigating role in reducing erosion, trapping transported sediment, and stabilizing gully slopes in a negative feedback cycle. Vegetation is an integral part of most channel evolution processes (Simon and Hupp 1992; Hupp 1992), including gully evolution (Gellis et al. 1995; 2001). Increasing vegetation with gully channels and networks can occur through removing or changing chronic disturbances inhibiting recovery (e.g., grazing or clearing) and thus promoting natural recovery, or by direct planting of vegetation within or around gully networks.

Recent gully erosion studies have documented the dominant role of recolonizing or planting vegetation (grass, shrubs, trees) in stabilizing gully floors and channels, increasing sediment deposition and promoting channel aggradation, reducing downstream sediment yields, and driving positive feedback loops that promote landscape recovery (Vanacker et al. 2007; Molina et al. 2009; Reubens et al. 2008; Reubens et al. 2009; Sandercock and Hooke 2011). Colonizing plants with specific anchoring traits on badland slopes can also be effective at increasing soil cohesion and resistance to erosion, which is important for more proactive rehabilitation efforts (Burylo et al. 2009). In rangelands of India affected by alluvial gully erosion, the destocking or careful rotational management of cattle has also been shown to result in the dramatic recovery of savanna vegetation within several seasons (Hudson 1987), including directly within gullies or ravines where stock have been excluded (Haigh 1984; 1998; Raizada et al. 2005). These benefits are in addition to the benefits of direct revegetation or afforestation of gullies and ravines mentioned below.

For alluvial gullies in the Mitchell River in northern Australia, Shellberg (2011) has documented both grass and Eucalyptus tree colonization onto gully inset-floodplains following gully scarp retreat, indicating the natural recovery potential. However, the influence of this vegetation on sediment storage and positive feedbacks toward gully stabilization remain unquantified, as are the influences of ongoing grazing on the full recovery potential of the vegetation.

In Queensland’s tropical rangelands, vegetation cover will most typically improve if cattle are excluded or dramatically reduced from an area (McIvor et al. 1995; Scanlan et al. 1996; Roth 2004; O’Reagain et al. 2005; Bartley et al. 2010a; 2010b; O’Reagain and Bushell 2011; Silburn et al. 2011). Most importantly however, the full exclusion of stock from gullied and scalded areas may or may not by itself result in vegetative or hydrological recovery over the short or long-term (Silcock and Beale 1986 cited in Bartley et al. 2010b), unless accompanied by other rehabilitation measures. This is especially true for gully erosion areas and scalded soils were topsoils have been lost and sodic sub-soils have been exposed (Pressland et al. 1988). However, long-term cattle exclusion experiments have significantly reduced soil and gully erosion on the extremely degraded “Springvale Station” in the Nogoa River catchment (Fitzroy River catchment, Qld) (e.g., Ciesiolka 1987; Silburn et al. 2011), which can be seen from satellite imagery (Figure 34). Thus, long time periods may be needed for soil and vegetation recovery.

Figure 34 A cattle exclusion area (centre photo) on the extremely degraded "Springvale Station" in the Nogoa River catchment (Fitzroy River catchment, Qld) where dramatic vegetation recovery and erosion reduction has occurred over the last two decades (-23.693012°, 147.456605°).

In the Burdekin catchment of northern Australia, Bartley (2010a; 2010b) documented that scalded soil areas immediately above gullies and on gully slopes did not respond to short-term improved Grazing Land Management (GLM), despite modest reductions to runoff from hillslopes above. However, long-term full cattle exclusion from hillslopes and gullies was not trialled to reduce downstream gully erosion rates and local grazing disturbance. Bartley (2010b) recommended alternative strategies to improve vegetation cover on scalded foot slopes and gullies near riparian zones, including fencing to fully exclude cattle and more intensive rehabilitation using mechanical intervention and proactive vegetation planting. However, it was noted that any intervention in these areas needed a cautious approach, since they were major sources of sediment and erosion could be exacerbated by some interventions. Rehabilitation of scalded hillslopes has been successful in semi-arid Australia using deep ripping and contour furrows, gypsum addition, and water ponding (e.g., Jones 1969; Cunningham 1974; Muirhead et al. 1974; Alchin 1983; Thompson 2008), but the application of these techniques to scalded patches fringing and within gullies is questionable. The same caution is needed for intensive gully rehabilitation, which has had mixed results of application, cost-effectiveness and physical success in sediment erosion reduction in Australia (Crothers et al. 1990; Bartlett 1991; Hadden 1993; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008; Miller 2008; Alt et al. 2009; Jolley 2009; Shellberg 2011; Section 7).

The natural vegetation recovery potential in alluvial gullies and the influence of vegetation in reducing alluvial gully erosion once initiated is a major topic of research needed across northern Australia over the long-term. Section 7.5.2 (cattle exclusion experiments) and 7.6.2 (direct revegetation experiments) of this report are significant steps towards this research.

7.5.2 Cattle Exclusion, Spelling, and Vegetation Recovery Trials in Alluvial Gullies in the Normanby Catchment

In order to rehabilitate alluvial gullies on a large scale in the Normanby catchment, an indirect/passive approach to rehabilitation will be needed due to costs and scale, in addition to more direct/intensive efforts around areas of strategic concern. An indirect/passive approach will need to remove chronic stressors from the savanna ecosystems and will rely on the natural resilience of perennial grass vegetation inside and upslope of gullies. Positive feedbacks mechanisms of vegetation recovery should increase soil protection and infiltration, reducing water runoff, reducing sediment erosion, and increasing sediment deposition (see Section 6). In order to increase natural vegetation growth via indirect/passive methods, cattle grazing, fire regimes and weed impacts to perennial grass growth must be carefully managed under alternative paradigms within river frontages and riparian zones (Section 6.5).

To reduce cattle grazing impacts in and around alluvial gullies, permanent exclusion fencing or at least wet season spelling using fencing will be needed (Section 6.5.2 and 6.5.4). For the worst eroded alluvial gully areas along riparian zones and river frontage (Figure 14; Figure 15), permanent cattle exclusion is likely needed with regular maintenance of fencing infrastructure and periodic mustering of wild cattle (Section 6.5.4). In large concentrated areas of gully erosion that are more difficult to permanently fence, seasonal, annual or tailored spelling of cattle could be a useful alternative if it has demonstrable improvements on vegetation and soil conditions in and around gullies (Section 6.5.2). Wet season spelling could also be a more practical alternative to exclusion in very productive soil areas where permanent exclusion of cattle would be economically prohibitive if all costs (internal and external) are taken into account.

In concentrated areas of gully erosion at the sub-catchment scale, taking large areas of relatively unproductive grazing land out of cattle production could be a viable option to create 'soil conservation areas'. However, government or market-based funding would be needed to compensate lease holders for their economic loss. Alternatively, government or market-based investments in 'improved pasture' on stable and productive soils not prone to gully erosion (e.g., basalt soils) could compensate for the loss of larger areas of much less productive land riddled with gully erosion. Hence, a trade-off approach could be trialled, where concessions are made and funding provided, for land use intensification in some areas capable of supporting it, while destocking highly eroding areas (e.g., Plate 17; Figure 152).

Fires must be managed appropriately in and around alluvial gullies along river frontage to promote indirect/passive revegetation recovery and improved cover. Instigating the most appropriate fire regime (timing, frequency, and magnitude) to maximise vegetation cover for soil stabilization will be key, such as periodic early-dry season fires and very infrequent intense fires in the early-wet season (Section 6.5.7). Alternatively, excluding fires altogether via fire breaks could be an option for sensitive riparian zones from which alluvial gullies usually initiate and propagate. However, exotic weeds might need to be managed accordingly to promote native grass cover, both with and without fire, unless particular weeds are deemed useful for soil erosion control and/or are a permanent part of the contemporary landscape (Section 6.5.8).

However, before widespread soil conservation practices are implemented to reduce alluvial gully erosion via indirect/passive vegetation recovery, experimental rehabilitation trials are needed to determine the effectiveness of specific measures, such as cattle exclusion, seasonal or annual spelling, and appropriate fire regimes, as well as the vegetation response of individual geomorphic units and gully types (e.g., Figure 35; Figure 36; Figure 37). Monitoring passive gully rehabilitation through vegetation recovery to show change will take time, likely one to two decades.


a) b)

Figure 35 Examples of improved cover of native kangaroo grass (*Themeda triandra*) following 5+ years of cattle exclusion on a) rounded gully slopes, and b) a gully scarp with only modest cover improvements compared to surrounding uneroded soils (middle Annan River).


a) b)

Figure 36 Examples of improved vegetation cover in gullies at a) a rounded gully where cattle and fire have been excluded for 5+ years, dominated by exotic stylo (*Stylosanthes spp.*) and native blady grass (*Imperata cylindrica*), and b) the same gully with some active gully scarps despite dense vegetation (middle Annan River).

a) b)

Figure 37 Examples of improved vegetation cover at a) a gully scarp where black spear (*Heteropogon contortus*) and blady (*Imperata cylindrica*) grass have improved following 2 years of cattle exclusion and b) a large gully scarp where grass cover improvements have been fairly isolated to gully floors, slumped soil blocks, and intact slopes (Normanby River at Kings Plain).

Cattle exclusion trials were implemented at four (4) sites in the Normanby catchment, with one (1) additional site proposed but not installed. The goal of these trials is to demonstrate and quantify over the long term (10+ years) the potential for vegetation recovery and sediment reduction in existing alluvial gullies after cattle exclusion. Multiple exclusion sites were established so as to capture the spatial and morphological diversity of alluvial gullies across the catchment (Figure 14; Figure 15; Figure 38). Study designs followed a before-after, control impact (BACI) design (Underwood 1994a; 1994b; Smith 2002) that monitored vegetation conditions at the plot scale and sediment erosion via repeat LiDAR. Assessment of vegetation and soil conditions at the plot scale followed protocols modified from Wilke (1997), Rolfe et al. (2004) and Karfs et al. (2009) (see Appendix 10.1 and 10.2).

Initial cattle exclusion fencing and “before” vegetation monitoring were conducted in 2012/2013. Repeat LiDAR topographic surveys were flown in 2009/2011. Initial “after” vegetation monitoring was conducted in early 2013. *Hopefully, funding will be forthcoming to enable ongoing monitoring of vegetation every year over the next 10 years.* Periodic LiDAR surveys every couple of years would also be useful for quantifying erosion change. Regardless, in 10 years it is recommended to revisit the cattle exclusion gullies and fully quantify changes that have been observed via vegetation surveys, repeat LiDAR, and analysis of fire history. Where data on “before” conditions are limited due to initial 2012/2013 efforts, more detailed vegetation and soil data could be collected in 10 years at control and treatment sites to better quantify changes, which will value add to initial efforts.

Some key questions this research can hopefully answer include the following.

- How does vegetation cover and species change over time in existing gullies with and without cattle exclusion?
- What is the influence of weed invasion into gully areas and does this have positive or negative influences on sediment erosion?
- How do vegetation changes vary by specific geomorphic units such as scarps, slopes, gully floor, intact upper floodplain, cattle tracks (pads), etc.?
- What are the complicating influences of fire?

- What are the complicating influences of native marsupial grazing?
- Are there detectable differences in cattle and animal track density over time?
- Does vegetation recovery help stabilise specific geomorphic units and structures?
- Are these experimental methods robust enough for proper quantification of long-term change?
- What additional information could be collected now or in the future (control/treatment) to value add to these existing data?

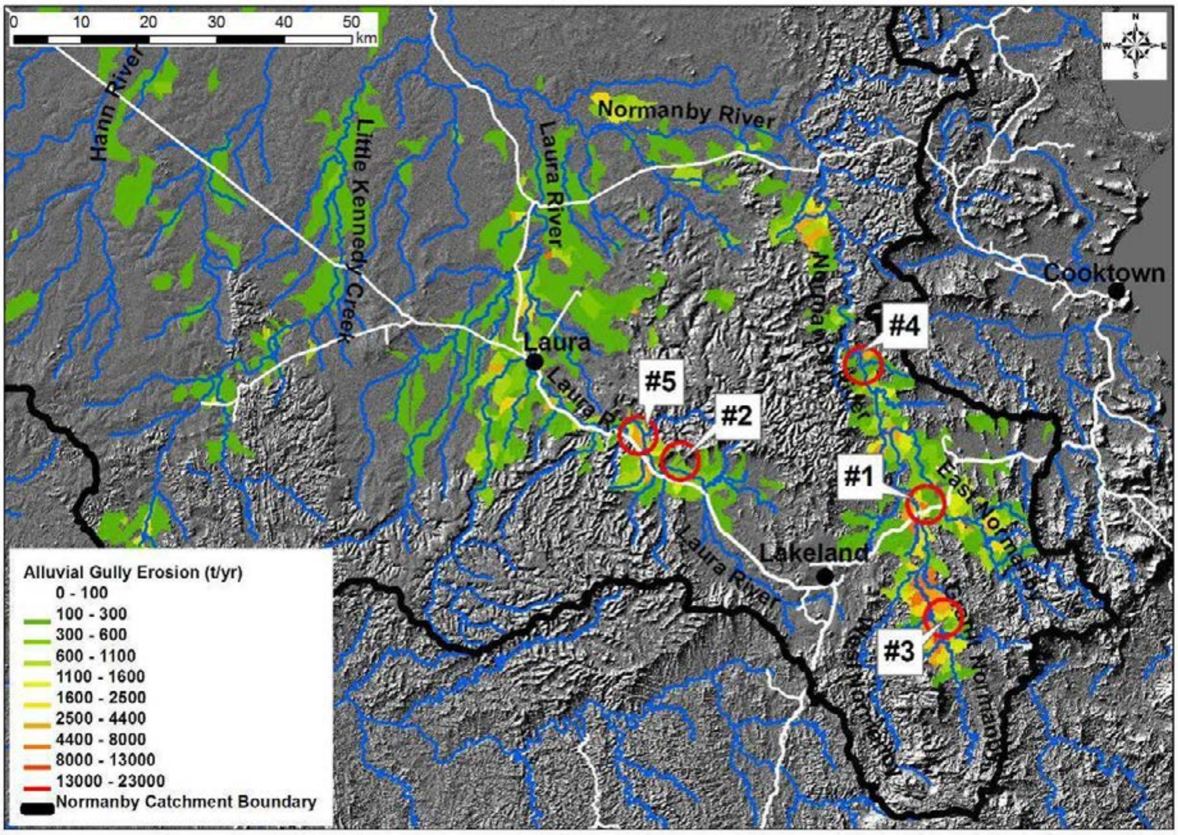


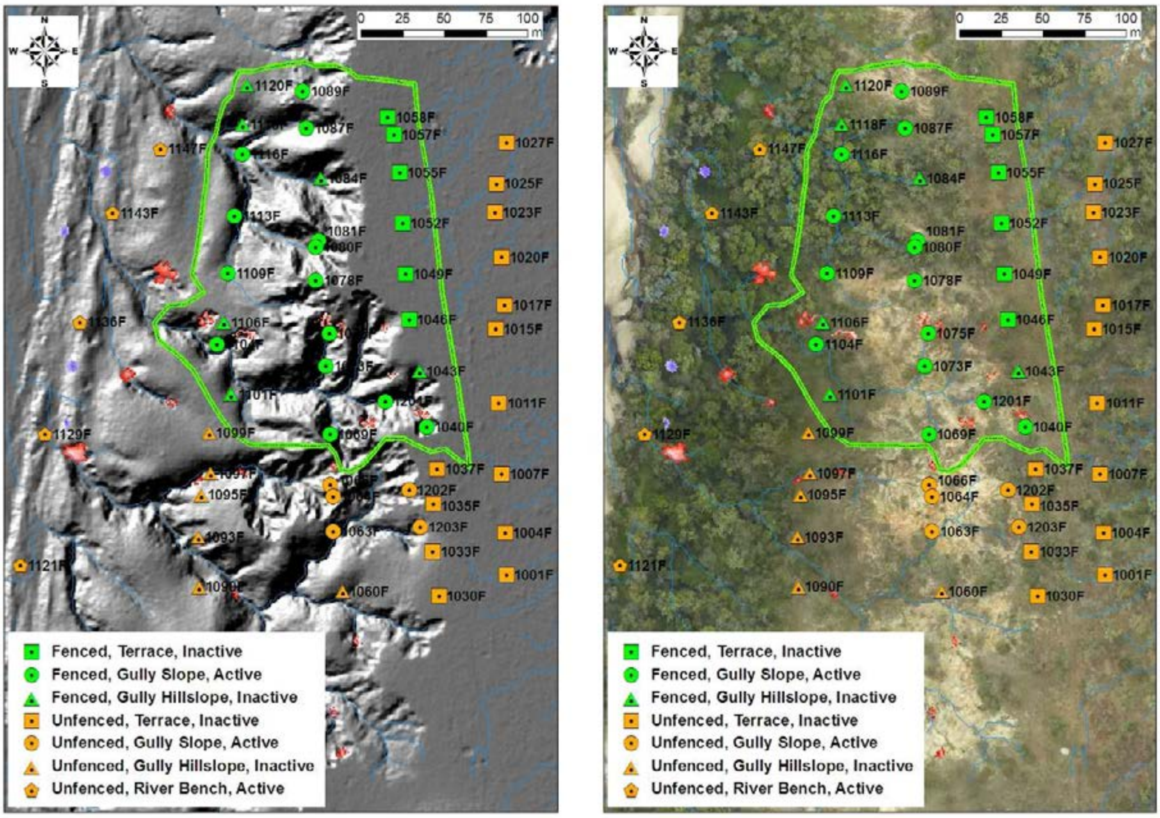
Figure 38 Distribution of sub-catchments with significant alluvial gully erosion (tonnes/year/subcatchment) in the Laura-Normanby catchment (from Brooks et al. 2013), and locations of fenced cattle exclusion experimental sites, #1) West Normanby (-15.762320°S, 144.976602°E), #2) Crocodile Paddock (-15.710042°S, 144.679232°E), #3) Granite Normanby (-15.896374°S, 144.994678°E), #4) Normanby River mainstem at Mosquito (-15.598804°S, 144.916466°E), #5) *proposed* at Laura River at Crocodile Gap (15.668992°S, 144.592765°E, see Section 7.11.5).

7.5.2.1 *Case Study 1: Cattle Exclusion from Bank Gullies at the West Normanby River*

On Springvale Station in the upper Normanby catchment, a 3 ha riparian area was fenced in October 2012 to exclude cattle from a series of alluvial gullies along the east bank of the West Normanby River, just downstream from the main highway bridge(s) (-15.762320°S, 144.976602°E; Figure 38; Figure 39; Figure 40). Gully erosion was initially monitored ('before conditions') using repeat airborne LiDAR surveys, completed in 2009 and 2011. *It is hoped funding for additional repeat LiDAR will be forthcoming in the future, especially within 10 years to document longer term change.* Repeat LiDAR will aid in the calculation of net erosion between years, and can also be used for comparison to changes in vegetation, fire and management conditions, and rainfall records at a nearby continuous rain gauge (East Normanby, DNRM). At the West Normanby site, a representative block of alluvial gully erosion through the riparian zone was selected to monitor changes in erosion and vegetation conditions before (Nov 2011) and after fencing (2012, 2013, etc.). Two main gully catchments are located inside the exclusion fence, one with overstorey tree vegetation and one without (Figure 39; Figure 40). A control gully without overstorey vegetation is located outside this fenced area, which was selected for monitoring change under status quo conditions with cattle access (Figure 40).

Figure 39 Aerial view (Nov-2011) of the West Normanby gully complex where cattle have been excluded. Note network of cattle trails on gully ridges and valleys.

In November 2011, vegetation monitoring plot locations were randomly selected along five transects parallel to the river from continuous points 10m apart along each transect to avoid repetition. In a few cases where large trees were encountered at random points, the plot location was adjusted slightly into adjacent more open pasture locations. Each transect was located at different elevations above the river and hence specific ecotones of vegetation. The upper two transects (1 & 2) are located on the high-floodplain (terrace) flats. Transects 3 & 4 are typical of gully channels, slopes, and interfluves, while transect 5 is along the active river bench (bonus data). Thus, vegetation plots were located both inside and outside the fence in comparable geomorphic locations. Overall, 24 plots were located outside the fence, and 26 inside the fence. Assessment of vegetation and soil conditions at plots followed protocols modified from Wilke (1997), Rolfe et al. (2004) and Karfs et al. (2009) (see Appendix 10.1 and 10.2). Vegetation data from these plots will be analysed using a before-after control-impact (BACI) study design (Underwood 1994a; 1994b; Smith 2002).



a) b)

Figure 40 West Normanby River below the Cooktown Highway (-15.762320°S, 144.976602°E) showing a) the location of the fenced cattle exclusion area and vegetation plots with a LiDAR background and b) the location of the fenced area and vegetation plots with an aerial photo background. Note that red areas in Figure 40a are zones of active gully erosion between 2009 and 2011 repeat LiDAR.

At each plot location, a permanent vegetation marker was established using a star picket. Each plot was 2m x 2m (4m^2) and identified by using a PVC grid centred on the star picket. Initial pasture conditions were assessed just before the break-of-season (November), when vegetation conditions are at their annual low before new rejuvenating monsoon rains. Within each plot area (4 m^2), a suite of semi-quantitative measurements and photographs were made of the pasture ground vegetation conditions, ignoring any large shrub or overstorey woodland conditions, following protocols modified from Wilke (1997), Rolfe et al. (2004) and Karfs et al. (2009) (see Appendix 10.1 and 10.2). These conditions included:

- Aerial projected % cover of all organic material
- Aerial projected % cover of individual cover components (leaves/sticks, dead matted grass, standing vegetation, standing weeds)
- % cover of just perennial grass

- # of species and species identification
- # of perennial tussocks
- Visual pasture yield estimate (standing biomass) from QDPIF picture templates
- Grass and weed species dominance
- Soil condition (erosion, deposition, crust integrity)
- Overall land condition rating (A,B,C,D)
- Detailed photographs of vegetation plot condition and species from multiple standard angles for future comparisons.

A sample template of the survey sheet is included in Appendix 10.1 and survey instructions in Appendix 10.2. In addition, plant species were collected and pressed at each plot for professional identification in March 2012, when the floristic characteristics of grass were best for proper identification. These samples have been identified by the Queensland Herbarium, and a species list is included in Appendix 10.6.

Overall, these measurements have been repeated semi-annually from 2011 to 2013. *Hopefully funding can be secured to resurvey these vegetation plots and LiDAR gully areas every other year, or at least every decade to detect changes over time, in addition to fence maintenance.*

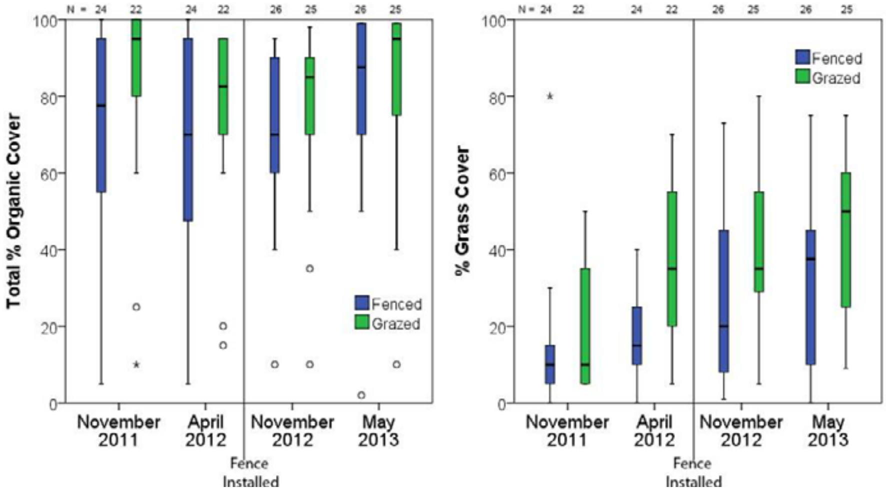
Fire is a management concern for this vegetation monitoring area at the West Normanby due to the dominance of grader grass on the high-floodplain (terrace). In Nov 2011, several large fires burnt large areas of this part of the West Normanby. However this area was spared due to the strong influence of the highway. Fires may influence vegetation conditions here into the future. However, annual fire breaks could be used to reduce the chances of fire, by back-burning the high floodplain from the west to east during the early-dry season. *This would require modest funding for the next 10 years and cooperation with the landowner who is open to experimentation.*

Preliminary Vegetation Change Results (2011-2013) West Normanby Exclosure

Vegetation conditions were monitored over two years and four seasons before and after fencing was installed at the West Normanby exclosure. Preliminary results indicated that both % total and % grass cover changed seasonally, as expected, with greater cover after the wet season (Figure 41). At both fenced and grazed sites, slight increases in % total cover were evident over the two year period, while major changes in % grass cover occurred from Nov-2011 to April-13 (Figure 41). Measured annual rainfall at the site was well below average for water year (WY) 2012 (630 mm), while annual rainfall during WY 2013 (950 mm) was average despite a very slow start to the wet season. These climate variations would have influenced grass cover, regardless of fence installation.

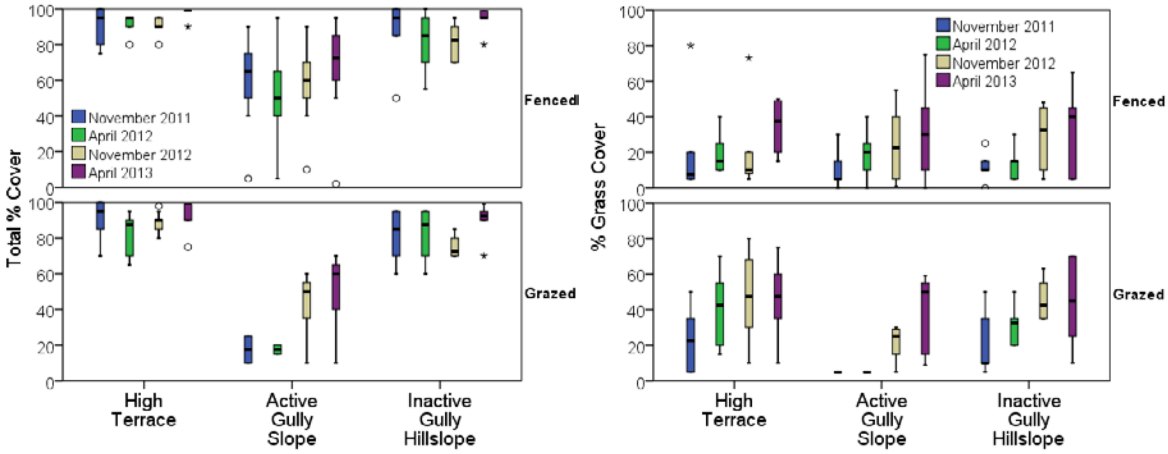
When vegetation cover is examined by different geomorphic units (high terrace, active gully slope, inactive gully hillslope) both inside and outside the fence, the general trends of increased cover by year and season are still evident (Figure 42). Cover on intact high terrace flats improved the most for % total and % grass cover, with the largest increase or jump in % grass cover occurring on fenced terrace flats after fence installation (Figure 42b, Fenced). Removal of cattle grazing on these flats contributed to this large increase. However, cover also increased at grazed (unfenced) sites due to improved rainfall conditions over time, such as with grass cover (%) increases on active and inactive gully slopes, both inside and outside the fence (Figure 42b).

These preliminary data display the usefulness of a before-after, control-impact (BACI) study design to understand changes over time from land management actions (e.g., fencing). Moreover, they highlight the need for long-term data over the next decade on these cover variables and others (e.g., biomass) to be able to tease apart the influence of management treatments (e.g., fencing) on vegetation and erosion, from natural variability due to rainfall or other variables. A decade of data of annual and/or seasonal conditions at each BACI plot will allow for more robust statistical analysis to be applied. These data and statistical analyses are needed in order to assess the natural resilience and recovery potential of vegetation and soil erosion conditions at alluvial gullies.



a) b)

Figure 41 Preliminary changes in cover inside and outside the West Normanby cattle exclusion site from 2011 to 2013 showing a) total % organic cover (grass, weeds, leaves, sticks, mulch) and b) % grass cover (standing perennial or annual grass).



a) b)

Figure 42 Preliminary changes in cover at different geomorphic units (terrace, gully, hillslope) inside and outside the West Normanby cattle exclusion site from 2011 to 2013 showing a) total % organic cover (grass, weeds, leaves, sticks, mulch) and b) % grass cover (standing perennial or annual grass).

Cattle/Animal Track (Pad) Surveys at the West Normanby Exclosure

Cattle/animal track (pad) locations and depths also were surveyed at the West Normanby along three transects through the gullied riparian zone to document changes over time due to cattle exclusion (e.g., Figure 43). Along each transect inside and outside the cattle exclusion fence, cattle/animal track locations were marked with a GPS where they crossed each transect (Figure 44). At these points, several track metrics were assessed including:

- % ground cover (grass and total organic)
- Number of vegetation tussocks per 2 m pad length
- Average width of the track
- Average depth
- Maximum depth
- Pad class (1 to 4)
    1) Abandoned Track
    2) Active Track, Un-incised (0 mm)
    3) Active Track, Incised (0-20 mm)
    4) Active Track, Incised (20-50 mm)
    5) Active Track, Gully Incision (>50mm)

Detailed photographs were also taken from vertical and oblique angles of each point (e.g., Figure 43). Differentiating wallaby pads from cattle tracks (pads) was difficult in some cases. Cattle tracks were often clear migration paths toward water that were roughly perpendicular to the river, often cut deeply into the alluvial soil. In contrast, wallaby pads were more erratic and discontinuous features, often shallower in depth. However, more subtle cattle tracks also were present as off-shoots of main tracks as cattle grazed along migration paths to the river. Changes over time from cattle exclusion should highlight differences between cattle and wallaby tracks (pads). Tracks should be surveyed into the future in association with vegetation plot surveys.

a) b)

Figure 43 Cattle track (pad) erosion examples from the east bank of the West Normanby River.

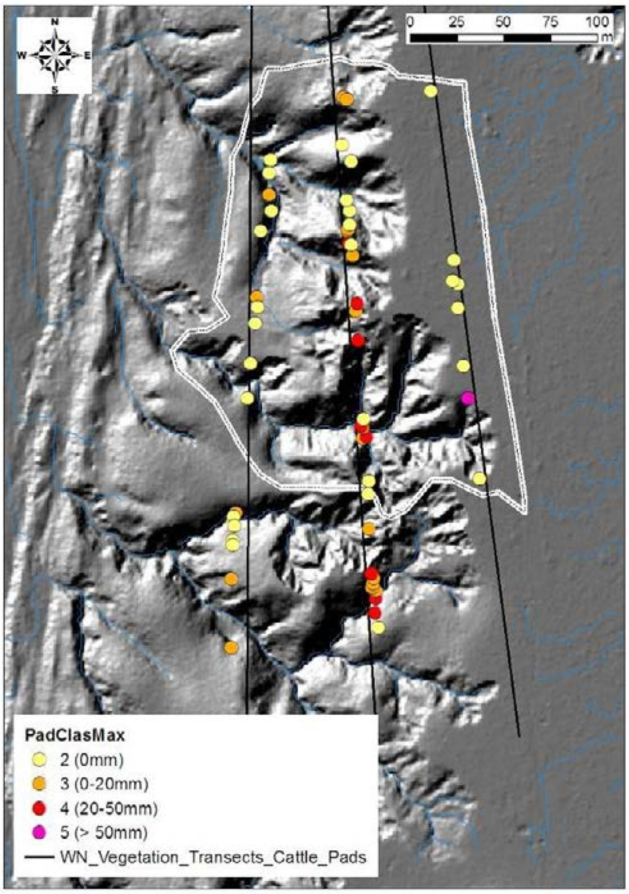
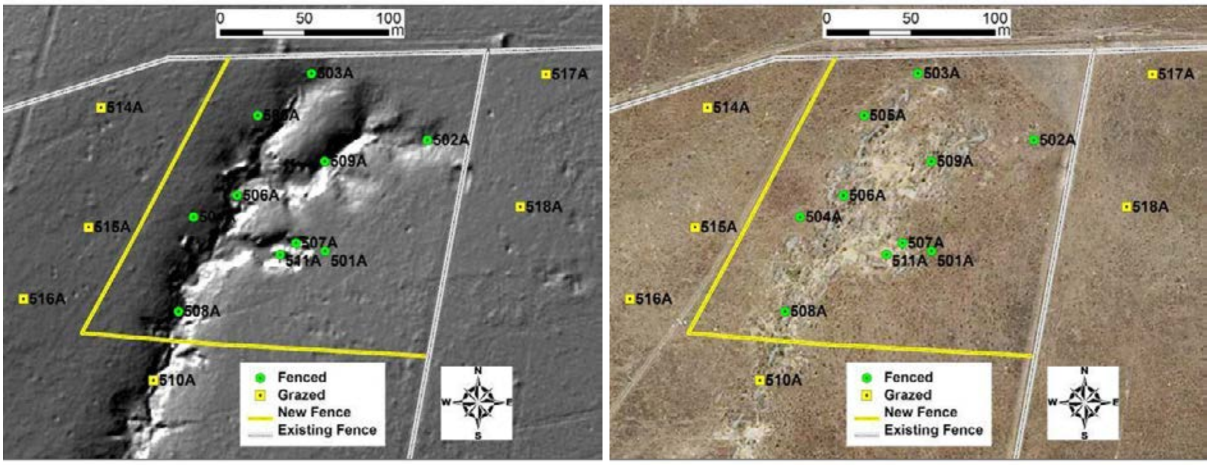


Figure 44 Cattle/animal pad locations in Dec-2011 crossed along three transects inside and outside the West Normanby exclusion fence.

7.5.2.2 *Case Study 2: Cattle Exclusion from Paddock Gullies near the Laura River*

At Crocodile Station, a 5 ha area was fenced from cattle in Jan 2012 in a large cleared paddock (Old Hay Paddock) affected by alluvial gully erosion (-15.710042°S; 144.679232°E; Figure 38; Figure 45). Vegetation and LiDAR erosion monitoring followed a similar BACI protocol and monitoring methods (Appendix 10.1 and 10.2). Ten (10) 4m^2 plots were randomly established inside the fencing exclosure without grazing as a treatment, and five (5) plots were located immediately outside the exclosure with grazing in the open paddock as a control. Eleven (11) additional plots also were located in an adjacent paddock and several small gully systems with grazing as a control. Vegetation plot data were collected before (Nov 2011) and after fencing (2012, 2013, etc.), while LiDAR data were collected in 2009 and 2011. Longitudinal profiles of the gully channel and headcut heights and positions were also surveyed with a total station in November 2011. Hopefully funding can be secured to resurvey these vegetation plots and LiDAR gully areas every other year, or at least every decade to detect changes over time.

Fire is *completely* excluded from these key paddocks at Crocodile Station due to their close proximity to the station house (i.e., no fires in the last 12 years, NAFI; Figure 29). However, episodic disturbance of the grass community does occur from biannual tractor ‘chaining’ of *Melaleuca viridiflora* seedling regrowth in the paddock. However, this minimally disturbs the grass understorey community present in open paddocks, but does disturb fragile soils when chaining through gullies and hollows. Over the next 10 years without ‘chaining’ of the Eucalyptus and Melaleuca seedlings in the cattle exclosure, tree regrowth should occur, which might compete with grass understorey vegetation for light, nutrients, and water. While trees can also help stabilise gullies (Shellberg 2011), their net competitive effects on grass species that are essential to erosion control are unknown at this site, which will be monitored over time. However, if a riparian buffer had been installed around this small hollow and gully before initial tree clearing in the 1970’s, then erosion might not have been so severe. Therefore, by installing a tree and grass buffer around this gully, along with cattle exclusion, it is hypothesised that the gully system will stabilise. Improvements in grass vegetation cover have already occurred with the exclusion of cattle and partial spelling of the adjacent paddock (Figure 46).



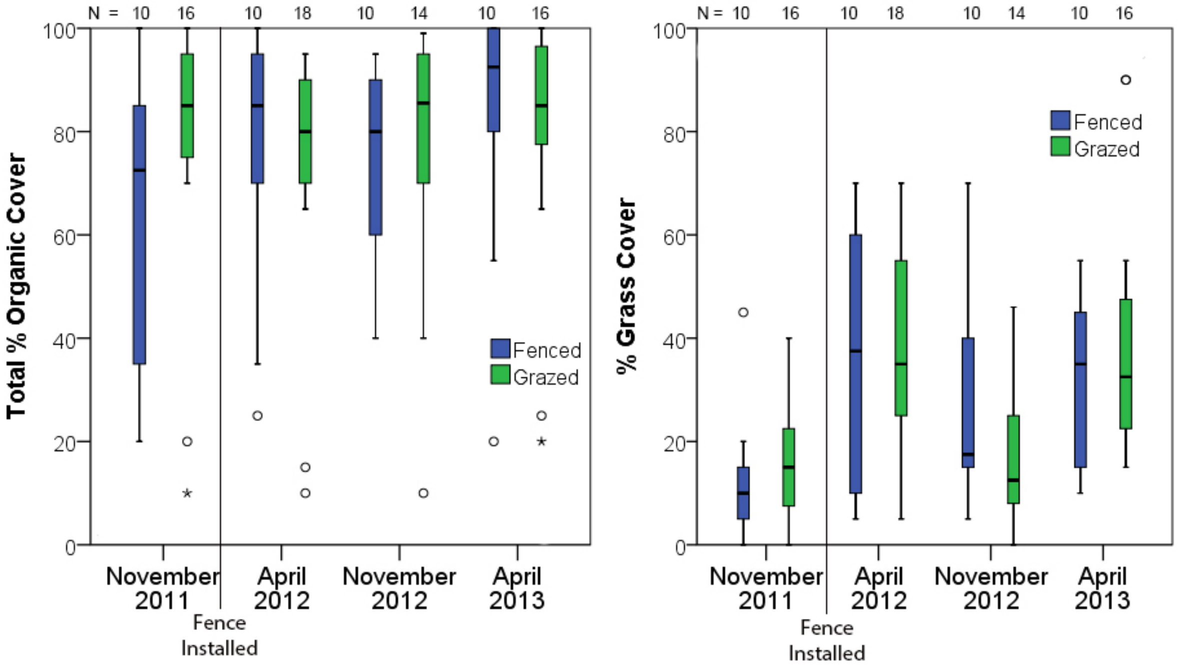
a) b)

Figure 45 Maps of the cattle exclusion fence in the ‘Old Hay Paddock’ at Crocodile Station (-15.710042° S; 144.679232° E) with a) LiDAR hillshade background and b) aerial photograph background showing locations of vegetation monitoring points inside and outside the exclusion area.

Preliminary Vegetation Change Results (2011-2013) Crocodile Paddock Exclosure

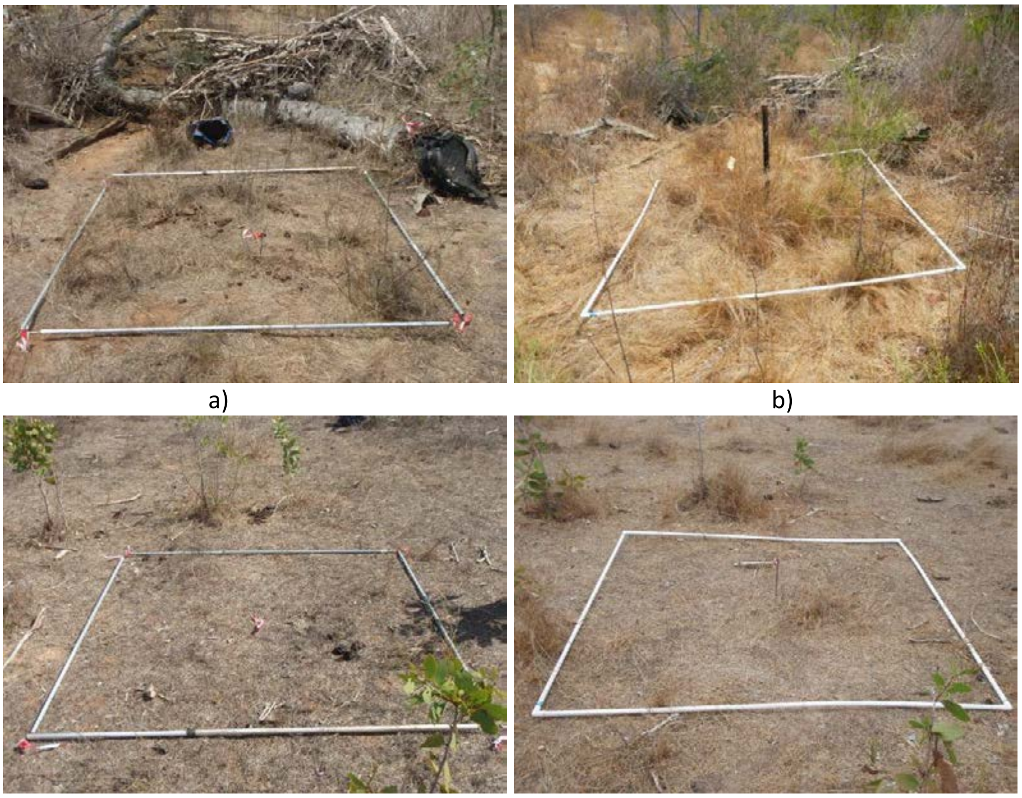
Vegetation conditions were monitored over two years and four seasons before and after fencing was installed at the Crocodile paddock exclosure. Preliminary results indicated that both % total and % grass cover changed seasonally, as expected, with greater cover after the wet season (Figure 46). Total cover at fenced sites within the gully area increased over time, while % total cover at grazed sites remained relatively constant (Figure 46a). Grass cover varied more over time and season, but with greater improvements over time within the fenced gully (Figure 46b; Figure 47). Measured annual rainfall at the site was below average for both WY 2012 (786 mm) and WY 2013 (741 mm) (Figure 105).

Long-term data over the next decade on these cover variables and others (e.g., biomass) will be needed to tease apart the influence of management treatments (e.g., fencing) on vegetation and erosion, from natural variability due to rainfall or other variables. This will help assess the natural resilience and recovery potential of vegetation and soil erosion conditions at alluvial gullies.



a) b)

Figure 46 Preliminary changes in cover inside and outside the Crocodile Station 'Old Hay Paddock' cattle exclusion site from 2011 to 2013 showing a) total % organic cover (grass, weeds, leaves, sticks, mulch) and b) % grass cover (standing perennial or annual grass).



a) b)

c) d)

Figure 47 Changes in vegetation cover and biomass at a) before fencing at Plot 508 gully bottom in Nov-2011, b) after fencing at Plot 508 gully bottom in Nov-2012, c) grazed control at Plot 515 hillslope in Nov-2011, d) grazed control Plot 515 hillslope in Nov-2012.

7.5.2.3 *Case Study 3: Cattle Exclusion from Distal Tributary Gullies along the Granite Normanby River on Springvale Station*

On Springvale Station in the Normanby catchment, a 2.3 ha gully complex (GNGC6) was fenced in January 2013 to exclude cattle from a distally draining gully flowing into a tributary of the Granite Normanby River (-15.896374°S; 144.994678°E; Figure 38; Figure 48). Initial vegetation plot surveys were conducted in November 2012 to define 'before' baseline conditions, following similar standard procedures as other vegetation surveys (Appendix 10.1 and 10.2). Vegetation plots were randomly located at 10 locations within the exclusion area, but were stratified by geomorphic unit (uneroded high terrace, active gully slope, inactive gully hillslope) (Figure 49). For comparison to the fenced treatment area, two additional gullies were monitored for comparison, one that was spelled (partially) from grazing for 1-2 years starting in 2013 and the other that was grazed as normal. Each of these gullies also had 10 vegetation plots that were randomly located but stratified by geomorphic unit.

- Exclusion (GNGC6) (10 Plots)
- Spelling (GNGC9) (10 Plots)
- Grazed (GNGC1) (10 Plots)

The unfenced but (partially) spelled gully (GNGC9) was located immediately adjacent to the fenced exclusion gully (GNGC6) in the Abbey Lea paddock and both drained into the same tributary (Figure 49). The unfenced and grazed gully (GNGC1) drained into a tributary on the opposite side of the Granite Normanby in Dead Dog paddock (Figure 48). At all sites, gully erosion was initially monitored ('before conditions') using repeat airborne LiDAR surveys, completed in 2009 and 2011. Hopefully funding can be secured to resurvey these vegetation plots and LiDAR gully areas every other year, or at least every decade to detect changes over time.

For additional distributed monitoring of pasture vegetation conditions between the (partially) spelled Abbey Lea paddock and the grazed Dead Dog paddock, ten (10) additional vegetation plots were established with 5 in each paddock on the uneroded high terrace surface. The plots were randomly located on either side of the main paddock fence, and pairs of plots were located approximately 1 km apart longitudinally down the Granite Normanby channel (Figure 50). The 3 vegetation plots each on the uneroded high terrace surface of GNGC1 (grazed, Dead Dog) and GNGC9 (spelled, Abbey Lea) can also be used for this more distributed comparison, totalling 8 plots in each of the spelled and grazed areas.

The overall objective of (partially) spelling the large Abbey Lea paddock from grazing for several years was to determine whether spelling could improve pasture conditions and vegetation cover in and around alluvial gullies and highly degraded pasture. If vegetation cover and associated metrics improve in and around alluvial gullies after spelling, it would support the hypothesis that sediment erosion from these gullies would also reduce as a result of spelling. Assessment of erosion at each plot in the spelled, grazed and fenced areas will help determine this, as could additional repeat LiDAR. Other more generally questions that could emerge from these trials include:

1. Does cattle spelling or full exclusion across highly eroded gully areas contribute to landscape recovery?
2. Can eroded, rugged, dissected areas with poor fencing infrastructure and maintenance really be spelled effectively?
3. How do short-term spelling benefits compare to longer-term complete cattle exclusion?
4. Is it reasonable from both sediment reduction and economic perspectives (including internal and external real costs) to spell or destock pastures degraded by gully erosion as a trade-off for improving already cleared pasture not severely threatened by gully erosion?

In order to fully answer these questions, additional physical, biological, and economic monitoring and modelling efforts will need to be invested in large concentrated areas of gully erosion such as the Granite Normanby on Springvale Station. However these initial monitoring efforts will be a useful start toward achieving this overall goal.

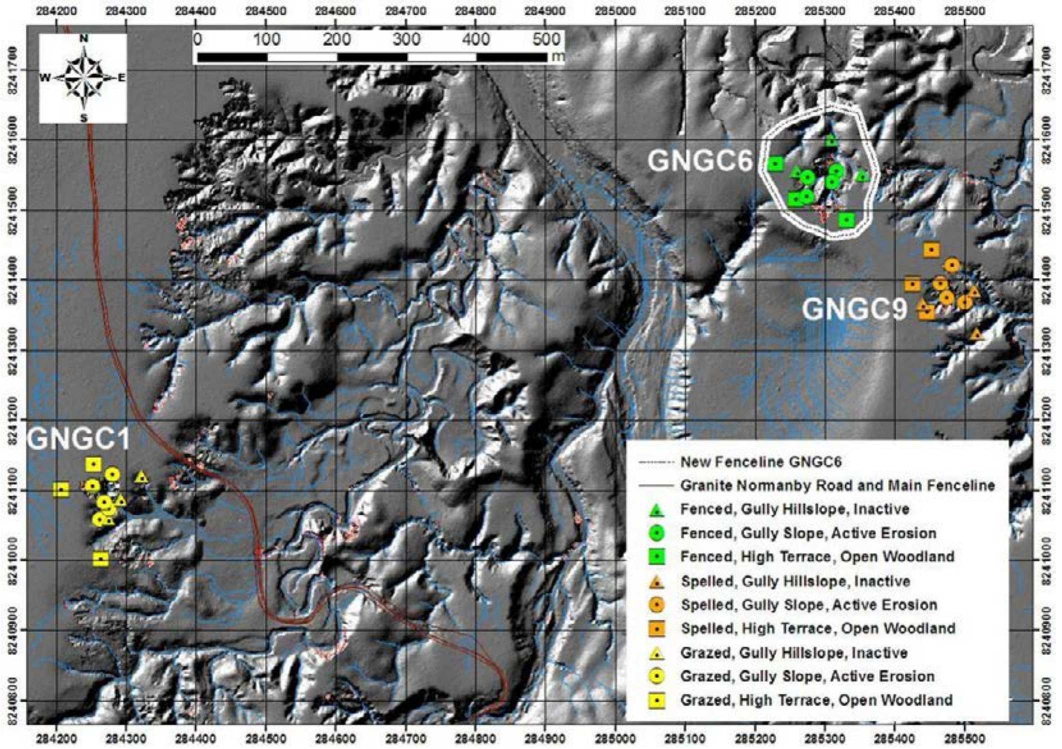


Figure 48 Hillshade LiDAR map of gully and vegetation monitoring sites on the Granite Normanby on Springvale Station. GNGC1 (Yellow) is being grazed as normal west of the main fence line and road (Brown), GNGC 9 (Orange) is being (partially) spelled for 1-2 years, and GNGC6 (Green; -15.896374°S; 144.994678°E) was fenced to exclude cattle for 10+ years. Note that red areas are zones of active gully erosion between 2009 and 2011 repeat LiDAR.

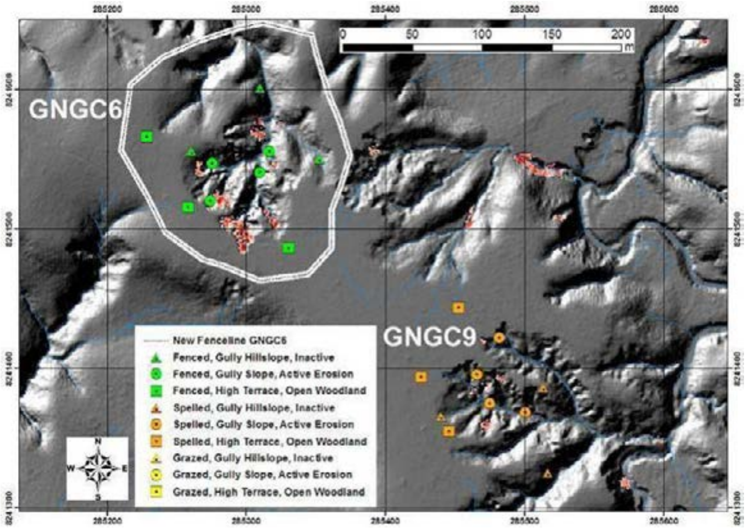


Figure 49 Hillshade LiDAR map of the cattle exclusion fence at GNGC6 (-15.896374°S; 144.994678°E) and neighbouring spelled GNGC9 on the Granite Normanby on Springvale Station. Note that red areas are zones of active gully erosion between 2009 and 2011 repeat LiDAR.

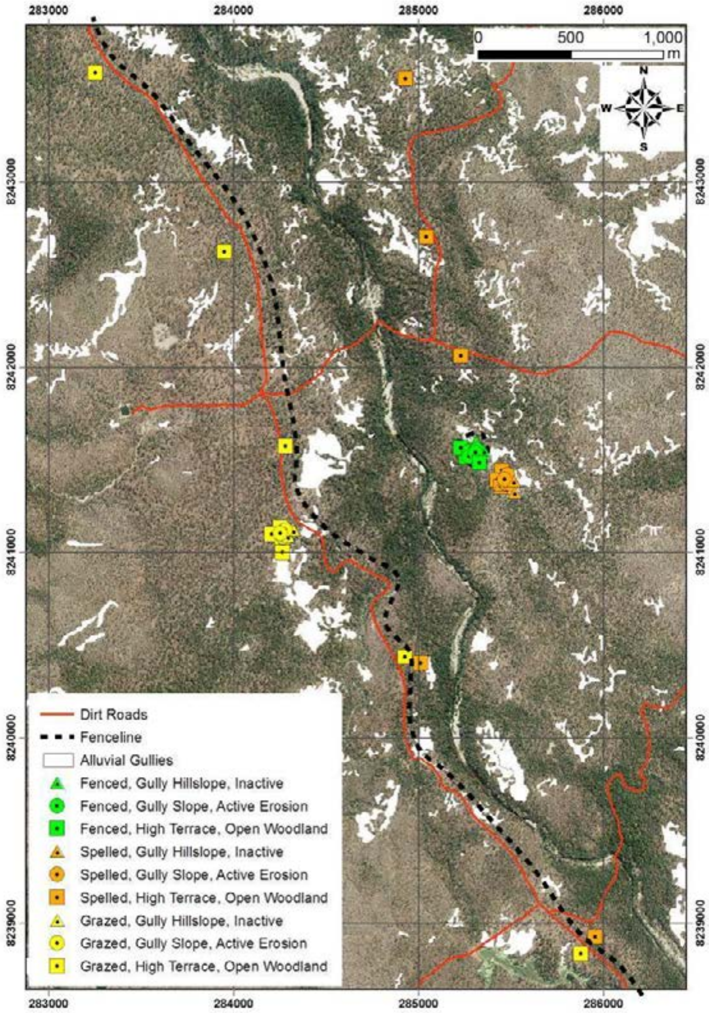


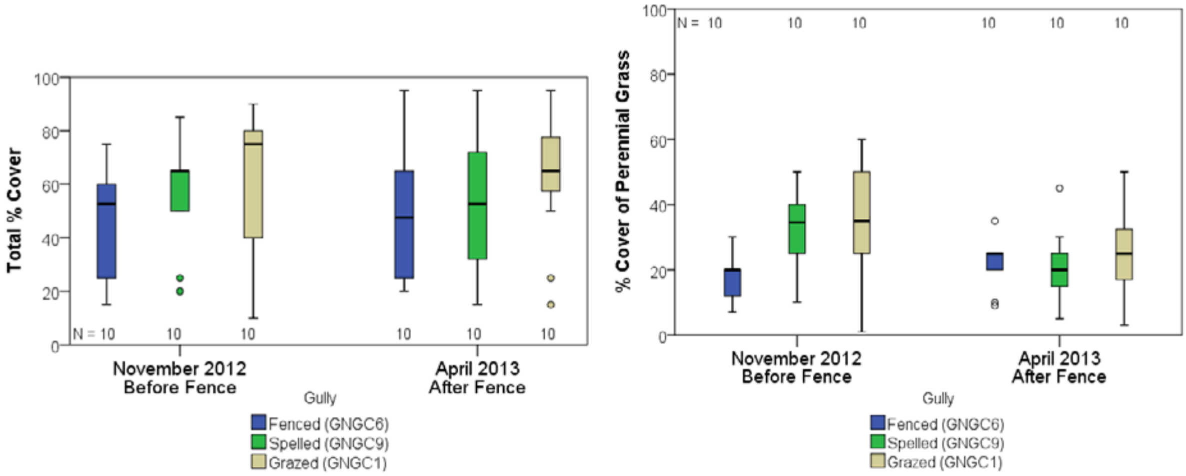
Figure 50 Aerial photo map of vegetation monitoring plot locations along the Granite Normanby in the spelled (Orange) Abbey Lea paddock to the west of the road and fence (dotted white line), and in the grazed (Yellow) Dead Dog paddock to the east of the road and fence. White areas are bare gullies mapped using Google Earth (Brooks et al. 2013).

Preliminary Vegetation Change Results (2012-2013) Granite Normanby Exclosure

Vegetation conditions were monitored over one year and two seasons before and after fencing was installed at the Granite Normanby exclosure, in addition to that monitored at the nearby spelled and grazed gullies. Preliminary results indicated that there was little change in % total cover at fenced, spelled or grazed sites (Figure 51). However, % grass cover increased slightly at the fenced site while grass cover declined at the spelled and grazed sites (Figure 51). The decline in grass cover at the spelled and grazed sites could be attributed to ongoing cattle grazing at these sites (Figure 53), with minimal attempts by the landowner to maintain the spelled area as cattle free or reduced grazing pressure.

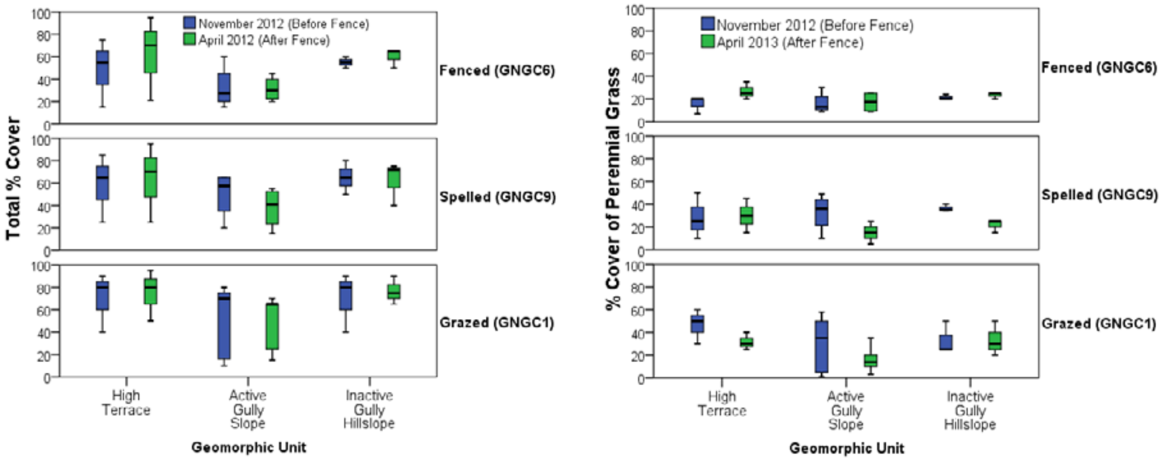
When vegetation cover is examined by different geomorphic units (high terrace, active gully slope, inactive gully hillslope), both % total and grass cover experience increased on the high terraces at the fenced site, while cover did not change or declined on spelled or grazed high terraces (Figure 52; Figure 53). On active and inactive gully slopes, % grass cover slightly increased or did not change in the fenced area, while conditions declined or did not change in the spelled and grazed areas (Figure 52b).

Long-term data over the next decade on these cover variables and others (e.g., biomass) will be needed to tease apart the influence of these management treatments (e.g., fencing, spelling, grazing) on vegetation and erosion, from natural variability due to rainfall or other variables.



a) b)

Figure 51 Preliminary changes in cover inside and outside the Granite Normanby cattle exclusion site from 2012 to 2013 showing a) total % organic cover (grass, weeds, leaves, sticks, mulch) and b) % grass cover (standing perennial or annual grass).



a) b)

Figure 52 Preliminary changes in cover at different geomorphic units (terrace, gully, hillslope) inside and outside the Granite Normanby cattle exclusion site from 2012 to 2013 showing a) total % organic cover (grass, weeds, leaves, sticks, mulch) and b) % grass cover (standing perennial or annual grass).

a) b)

Figure 53 Differences in grass cover and biomass between the fenced gully (Left, GNGC6) and the 'spelled' area (Right, GNGC9) on the high terrace of the Granite Normanby. Note the high stems and seed heads of native black spear grass (*Heteropogon contortus*) on the left of b).

7.5.2.4 Case Study 4: Cattle Spelling from Bank Gullies on the Normanby River

On Kings Plain station, the Reef Rescue cost-share program with a local landowner repaired a riparian fence line and 44ha cattle holding paddock at Mosquito Yards (-15.598804°S; 144.916466°E; Figure 54). The objective was to reduced cattle grazing along the high bank of the Normanby River riddled with alluvial gullies, as well as provide infrastructure for improved mustering and spelling of the back paddocks of Kings Plain. The land manager has initiated the spelling of the back quarter (1/4) of the property over the 2012-2014 period to reduce mustering overhead costs and allow the country to be spelled and recover. However spelling relies highly on the construction and maintenance of flood fences across the Normanby River, which to date have been poorly maintained.

The fencing of Mosquito Yards (Figure 54) has allowed for essentially a 'reverse' cattle exclusion experiment. The land outside the fences is currently being spelled, while land inside the fence will periodically have cattle during muster times as well as by drawing cattle into the yard via spear gates and feed supplements. To monitor vegetation changes over time, the land manager installed permanent photo points (star pickets) in 2009 to document before conditions; however retaking these photos annually has not occurred and the photo points were not focused on gullies.

In November 2012, permanent vegetation plots were installed in/around gullies inside and outside the fence (Figure 54). Vegetation surveys following similar standard procedures (Appendix 10.1). Six (6) vegetation plots were installed inside the fence, and 6 outside. Plots were randomly located but were stratified by geomorphic unit (uneroded high terrace, active gully slope, inactive gully hillslope) (Figure 54). Erosion ‘before’ conditions also were surveyed by repeat LiDAR in 2009 and 2011.

To compliment these data across a larger spatial area, fifteen (15) additional vegetation plots were installed, with 5 in each of three different paddocks (Ranch, 12-Mile, Dingo paddocks). In November 2012, these plots were located on uneroded flat terraces above major gullies. Vegetation changes over time at these sites should highlight differences between spelled and grazed paddocks.

Hopefully, funding can be secured to resurvey these vegetation plots and LiDAR gully areas every other year, or at least every decade to detect changes over time.

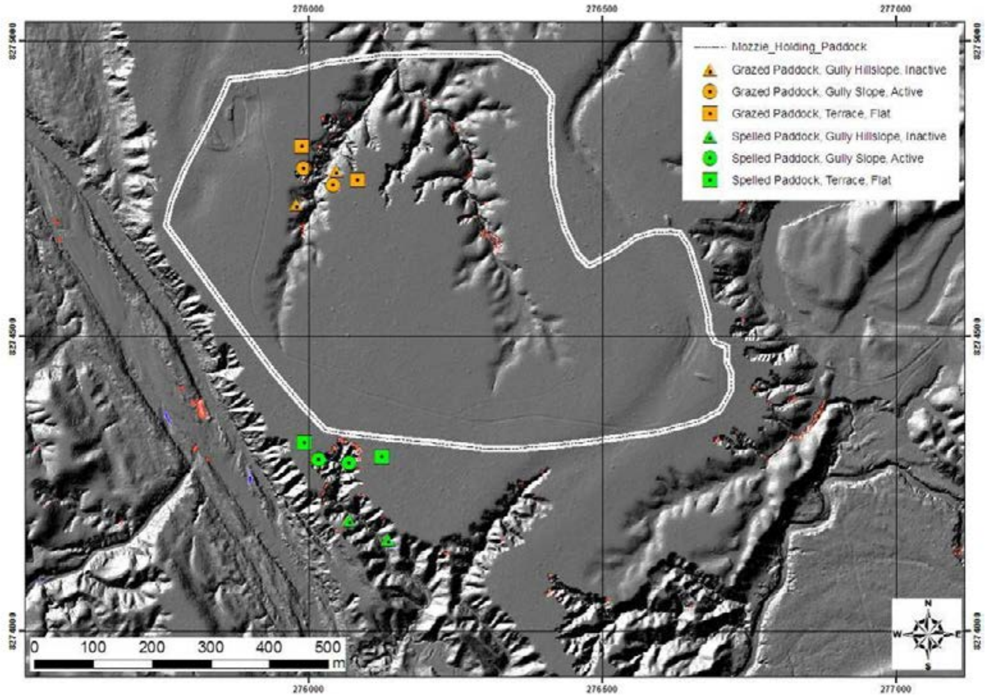


Figure 54 Hillshade LiDAR map of vegetation plot locations and the cattle holding paddock (Mosquito Yards) at Kings Plain, with cattle grazing inside the paddock and (partial) cattle spelling outside the paddock. Note that red areas are zones of active gully erosion between 2009 and 2011 repeat LiDAR.

7.5.3 Reef Rescue Projects on Riparian Fencing and Cattle Exclusion in the Normanby

Between 2008 and 2013 in the Normanby catchment, 11 riparian fencing projects to exclude cattle were implemented through the Reef Rescue Program in cooperation and cost-share with local landowners. These projects have excluded cattle from 76 km of riparian zone protecting 8698 ha (RR project data, Isha Segboer personal communication). Most of these had standard water quality benefits, such as directly reducing animal nutrients from entering streams, improving the integrity of the riparian zone for healthy vegetation cover, reducing stock trampling of the riparian zone, etc. However some also had the added potential to reduce the initiation of alluvial gullies by removing cattle disturbances such as tracks (pads) and vegetation consumption. Where alluvial gullies already exist, these riparian fencing programs also could aid in the indirect/passive vegetation recovery in and around gullies that promotes their stabilization.

All these riparian fencing projects were worthwhile in theory to achieve multiple water quality and riparian benefits. However, none were monitored in detail to determine the extent of any water quality benefits. Any benefits or potential impacts are assumed. Some actually accelerated overall soil erosion and gullying through unintended consequences, apathy, and/or poor planning and implementation (see Section 7.15 and Figure 144). Most projects had permanent oblique photo points installed to help track changes in vegetation and perhaps erosion over time. However, only a few of the photo points were actively resurveyed annually by the landowners, as agreed upon in the original contracts. This has hampered any local learning opportunities. Furthermore, most photo points were located on floodplain flats or uneroded riparian slopes, which is adequate for monitoring general changes in vegetation cover, but not for gully erosion. Since alluvial gully erosion in riparian zones is a major source of sediment in the Normanby catchment (Brooks et al. 2013), these gully areas within newly fenced riparian zones also should have been targeted for qualitative photo monitoring.

These riparian fencing projects also could have been sites for more intensive quantitative monitoring of vegetation and erosion conditions (e.g., Appendix 10.1 and 10.2). Repeat LiDAR topographic surveys in a few locations could have also documented changes in gully erosion. Unfortunately for BACI experiments on gully erosion, most riparian fencing sites were unsuitable for detailed study due to the lack of suitable controls outside the riparian fence, along with quantitative data on 'before' conditions. However this was a result of the nature of these riparian fencing projects, to exclude cattle from the entire river corridor under the assumption that things would improve from some undefined 'before' condition. These facts were the main motivation in 2011 for installing multiple, small, cattle exclusion fences as trials to quantify changes in vegetation cover and erosion over 10+ years (see Case Studies 1 to 5 in Section 7.5.2 above).

7.6 Direct Revegetation on In-Situ Surfaces

7.6.1 Literature Review

Vegetation is often directly planted into eroding gully channels to promote recovery, often in association with other mitigating features such as grade control structures, terracing and slope regrading, and organic and chemical soil amendments (see below). Caution should be exercised, however, when implementing such strategies, to determine the appropriate stage of channel evolution that vegetation replanting (or other intervention) should be undertaken. The success of plant establishment is linked to geomorphic stability and micro-site conditions (Simon and Hupp 1992; Hupp 1992; Reubens et al. 2008; Reubens et al. 2009), and major geomorphic change associated with early stages of channel evolution can destroy premature rehabilitation efforts. However, early intervention with vegetation or other measures could also slow or reduce future erosion and gully development.

Bioengineering intervention has often been used in gully stabilization to potentially overcome some of the geomorphic evolution and plant establishment concerns (NRCS 1992; NRCS 2007c). Completely new habitat and geomorphic conditions are often created mechanically for direct planting, in the hope that future vegetation establishment will stabilise the soils and offset any additional tendency for geomorphic change (NRCS 1992). Many techniques and materials can be utilised, such as mechanical regrading associated with live staking, live fascines, or live branch packing of woody shrubs in addition to direct planting of grasses (NRCS 1992). For example, the perennial grass vetiver (*Chrysopogon zizanioides*) from Asia is deep-rooted, non-invasive (generally sterile), and versatile, leading to its use around the world to stabilise soils and slopes (Gray and Sotir 1996; Mickovski and van Beek 2009; Jolley 2009). It is most often used in combination with other bioengineering methods such as slope regrading. In an effective design at gully slope stabilization, Ndona and Truong (2005) document the complete regrading of a gully complex using slope terracing and the planting of vetiver hedge rows along contours to maintain long-term stability. Vetiver has also been used in northern Australia for erosion control (Jolley 2009), but it is labour intensive as it must be planted by hand using cuttings.

7.6.1.1 <u>Australia</u>

In Australia, the use of vegetation planting for rehabilitation of gullies and tunnel erosion has aimed at re-establishing perennial grass and savanna woodlands to maintain a hydrological balance, prevent excess surface and sub-surface water runoff, and reduce soil erosion (Boucher 1990; 1995). Revegetation has often been conducted in concert with chemical amelioration or more invasive structural manipulation (see Section 7.13), making the isolation of the vegetative effects difficult.

In northern Australian tropical savannas, large-scale revegetation and soil stabilization efforts in the Ord (WA), Fitzroy (WA), Victoria (NT) and other catchments since the 1960’s have had mixed results in reducing soil erosion from rangelands degraded by overgrazing and gullying. In the Ord River catchment, destocking cattle, eradicating feral animals, contour ploughing of hardened soils, and seeding exotic shrub and grass species on denuded interfluves, shallow hillslopes and alluvial levees was successful at increasing ground cover and infiltration and reducing runoff (Hudson 1987; Tongway and Ludwig 2002;

Payne et al. 2004). Dramatic changes in vegetation cover occurred such as increases in native grasses, but altered species diversity and proliferation of exotic species remains problematic (Payne et al. 2004). However, efforts at stabilizing gully floors and head scarps using vegetation and structure were more sporadically conducted with generally poor results (Tongway and Ludwig 2002; Payne et al. 2004). This is unfortunate as gully erosion was and continues to be the dominant source of sediment in the Ord catchment, and these management interventions did not address gully erosion (Wasson et al. 2002).

In the Fitzroy River catchment (WA), similar mechanical and vegetative rehabilitation efforts of severely degraded alluvial river frontage (Payne et al. 1979) also had mixed results both environmentally (Western Australian Department of Agriculture 1981; Wasson et al. 2002) and economically (Wilcox and Thomas 1990). In the neighbouring Northern Territory, Sullivan and Kraatz (2001) document numerous successes and some failures of rehabilitating degraded pastures with mechanical intervention and reseeding. They concluded that the most cost effective solution for pasture rehabilitation was to exclude stock and let the area naturally regenerate. Furthermore, preventing degradation was preferable over rehabilitation due to costs and difficulty in repairing land and pasture.

7.6.1.2 United States

In the south-eastern United States, soil and gully erosion were dramatically accelerated following forest clearance, agricultural development, and cotton farming in the 1800's (Trimble 1974; Galang et al. 2007) with landscape recovery and reforestation occurring after farm abandonment after the 1920's. In South Carolina, Law and Hansen (2004) describe a long-term (80+ yr) governmental program of landscape rehabilitation following severe land degradation and gully erosion from early agricultural settlement. Rehabilitation focused on afforestation, revegetation of eroded gullies and slopes with native species, use of fertilisers to promote vegetation establishment, and where applicable, mechanical or structural measures within gullies were used to aid vegetation establishment and landscape recovery. Development of multi-stakeholder funded native plant nurseries and revegetation programs was a key to dramatic landscape recovery.

7.6.1.3 France

On steep badlands in France eroding into marls (lime-rich mudstones), revegetation and afforestation of highly eroded catchments has reduced sediment yields by an order-of-magnitude, which is a result of both water yield reductions and slope stabilization (Lukey et al. 2000 Mathys et al. 2003). More recent experimentation has focused on vegetation barriers (strips or buffers) used for trapping sediment eroding off badland slopes. Rey (2004) documented that low shrub and herbaceous vegetation barriers placed on the bottom of eroding slopes could trap most of the detached sediment. The minimum vegetation barrier area was 20% of the upslope eroding area for effective sediment trapping. Scaled to larger eroding gully catchments, targeted vegetation barriers could be effective at reducing sediment yields and promoting gully rehabilitation (Rey 2004).

7.6.1.4 New Zealand

In New Zealand, large-scale reforestation efforts with exotic conifer trees have been implemented over the last 50-years to reduce chronic gully erosion and sediment yield on steep terrain following native forest clearance post-European settlement (Marden et al.

2005; Parkner et al. 2006; Marden et al. 2011). Several research studies have documented that intensive tree planting in gully catchments has reduced both water and sediment yields by >30% each (DeRose 1998; Gomez et al. 2003; Herzig et al. 2011). Tree planting on both hillslopes above gullies and within existing or developing gullies was essential for sediment yield reduction (Betts et al. 2003; Marden et al. 2005; Herzig et al. 2011). Trees on hillslopes reduce soil moisture, pore water pressure, mass wasting, water yields to gully catchments, while reforesting existing or newly developing gullies reduces sediment yields more directly. However, reforesting gullies in isolation was deemed ineffective without addressing upslope hillslope water production. These studies highlight the importance of catchment-scale vegetation management for gully control and sediment yield reduction.

7.6.1.5 China

In China, large catchment-scale efforts at reducing soil and gully erosion in the Loess Plateau Region and elsewhere have utilised widespread revegetation and afforestation programs across space and time to stabilise gullies and hillslopes and reduce downstream sedimentation (Chen et al. 2007). Most revegetation efforts (tree and grass planting) were also implemented and monitored in concert with other stabilization techniques, such as the installation of check dams, sedimentation reservoirs, contour berms, surface water diversion ditches, and terracing, in addition to changes in land use (Huang et al. 2003; Zhang et al. 2008). Revegetation efforts have focused on hillslopes and to a lesser extent on revegetating gully bottoms and sidewalls (Chen and Cai 2006), despite these areas being the dominant sources of sediment (Li et al. 2003). After decades of implementation and monitoring, numerous studies have documented reductions in both water and sediment yield at the catchment scale from cumulative efforts (Huang et al. 2003; Chen and Cai 2006; Zhang et al. 2008; Rustomji et al. 2008). Once decoupled from climatic variations, reductions in *water yield* can largely be attributed to reservoir (dam) storage (Zhang et al. 2008) and afforestation of headwater areas (Huang et al. 2003a; 2003b). Causes of *sediment yield* reductions are more complex due to the interactions of multiple measures. Thus, the exact influence of the revegetation measures on gully stabilization and sediment yield remains uncertain, with the structural trapping of sediment by dams likely dominating observed sediment reductions to date (Zhang et al. 2008; Rustomji et al. 2008).

Furthermore in China, the success in establishing trees and plantations during afforestation efforts to control erosion have also been mixed, with many areas experiencing a die back of planted trees due to low rainfall and soil moisture availability (Xu et al. 2004; Trac et al. 2007; Cao et al. 2010). Planting species that are better adapted to local environments (in China's case shrubs and steppe species) is the key to long-term sustainable rehabilitation (Cao et al. 2010; Chen 2010).

7.6.1.6 India

In India, agricultural production for subsistence farming is vital for community wellbeing along the riparian zones of major rivers ravaged by "*ravine*" erosion (*sensu* Haigh 1984; 1998; Yadav and Bhushan 2002). This form of gully erosion into alluvium is akin in form and process to alluvial gully erosion in Australia (*sensu* Brooks et al. 2009). These alluvial ravines next to major rivers have been well documented in terms of causal factors such as climate, dispersive alluvial soils, tectonics, and land use (overgrazing, deforestation, agriculture) (Sharma 1982; Singh and Singh 1982; Sharma 1987; Singh and Agnihotri 1987; Singh and

Dubey 2000). Soil conservation measures and gully (ravine) rehabilitation efforts have been extensive since the 1950's in India (Haigh 1984; 1998), with efforts mainly focused on afforestation, agroforestry, and managing intensive agricultural systems (Yadav and Bhushan 2002; Yadav et al. 2003). The establishment and management of vegetation systems in gullied lands has the dual goals of 1) maintaining productive agricultural/agroforestry output for human needs via crop diversification, and 2) improving water retention and management during rainfall, infiltration, runoff, and channel flow processes (Bhushan et al. 1992; Narayan et al. 1999; Yadav and Bhushan 2002; Yadav et al. 2003). The complete destocking of cattle from ravines and gullies has also been shown to result in the dramatic recovery of grasslands (Haigh 1984; 1998; Raizada et al. 2005). Similar to China, often these agroforestry management systems in India have included additional physical measures to retain, infiltrate, and dissipate water through contour berms, terracing, mechanical slope regrading, and channel grade-control structures.

7.6.1.7 Summary

This literature review from a variety of different landscape and climate zones around the world highlights the importance and potential of using vegetation management and revegetation techniques to improve grass and tree cover to reduce gully erosion and sediment yields. Large-scale vegetation management and revegetation efforts will needed for significant results at the catchment scale.

7.6.2 Direct Grass Planting of In-Situ Gully Surfaces in the Normanby Catchment

7.6.2.1 Appropriate Grass Species

Grass is the preferred type of vegetation cover in an around alluvial gullies in savanna ecosystems in northern Australia, because its leaves and roots can effectively protect and bind the soil surface from raindrop impact and overland flow, and reduce gully initiation (see Section 2). While trees are also important at binding both surface and sub-surface soils together in and around alluvial gullies (Shellberg 2011), they are less effective at providing high ground surface cover and root cohesion at the soil surface.

For any rehabilitation or restoration project, the most appropriate vegetation seeds to use for replanting are native species and especially local varieties. In many instances it is not practical to obtain local varieties either due to the time and cost required for collection, or difficulty in collection. However, the added success and vigour of locally sourced genetic varieties may outweigh the increase in cost or time of local collection. Many commercial sources are now available for obtaining native seed, often with the variety tailored to specific areas. This is becoming increasingly common with native grass seeds in Queensland and Australia, where both commercial and government operations are generating seeds for rehabilitation purposes such as mine area reclamation and ecosystem recovery (e.g., Queensland Department of Agriculture Fisheries and Forestry).

In the upper Normanby catchment, the two native grass species that were dominant pre-European settlement along floodplains and alluvial flats were kangaroo grass (*Themeda triandra*) and black spear grass (*Heteropogon contortus*) (Weston 1988; Partridge 1995), with the latter becoming more common after cattle were introduced to the region (Pressland et al. 1988; Partridge 1995; Crowley and Garnett 1998, 2000). However many other species of native grass are/were also common across the Normanby catchment (Weston 1988; Neldner 1997). Some could be appropriate for erosion control, such as native blady grass (*Imperata cylindrica*), which is excellent for erosion control and under-represented as a protected plant community on floodplains on Cape York Peninsula (Weston 1988; Neldner et al. 1997). For this project in the Normanby catchment, the following native grass species were trialled in small scale revegetation efforts.

- **Kangaroo grass:** (*Themeda triandra*) (perennial native grass)
- **Black spear grass** (*Heteropogon contortus*) (perennial native grass)
- **Queensland Blue grass**: (*Dichanthium sericeum*) (perennial native grass)
- **Blady grass**: (*Imperata cylindrica*) (perennial native grass)

However often for rehabilitation efforts, utilization of exotic but naturalised and non-invasive species can be appropriate. In Queensland, this is the case with some exotic grass pasture species that are already naturalised and widespread across the state and are not generally considered pest invasive species (but not always). For example, some exotic grass species have been specially designed and introduced for improved erosion control through their dense stoloniferous roots (e.g., *Urochloa mosambicensis var. Saraji*). For this project in the Normanby catchment, the following exotic grass and herb species were utilised in revegetation efforts.

- **Indian Bluegrass**: (*Bothriochloa pertusa var. Bowen*) (perennial exotic grass)
- **Sabi Grass:** (Urochloa mosambicensis var. Saraji and) (perennial exotic grass)
- **Japanese Millet**: (*Echinochloa esculenta*) (annual exotic grass)
- **Verano Stylo**: (*Stylosanthes hamata*) (perennial exotic herb)

7.6.2.2 Direct Hand Sowing

Qualitative observations of the germination and establishment success of directly hand sowing grass seed on bare gully surfaces resulted in mixed but generally poor results. For example, following the installation of grade control structures at Crocodile Station (CRGC1-34), exotic sabi (*Urochloa mosambicensis*) and Indian bluegrass (*Bothriochloa pertusa*) grass were hand sown over the gully floor, gully walls (sodic soils) and uneroded flat surface (non-sodic) at an equivalent rate of ~50 kg/ha (Figure 55a). Sowing was conducted in the early-wet season after some initial rainfall. On the flat uneroded surfaces, exotic seed was lightly raked into the soil and covered with a thin layer of hay mulch. After the wet season progressed, seed germination and establishment occurred on the uneroded flat surfaces and gully floor, and to a lesser extent in a few areas of the gully wall (Figure 55cde). Erosion was fairly minor during the first wet season (Figure 55a-d). By one year later after an extra-long dry season but new wet season rains, the grass cover was virtually non-existent on the gully walls and gull floors, and was growing poorly with sparse cover on the uneroded flats (Figure 55e). However, by the end of the second wet season, sporadic grass was again growing on the flat surfaces, but not on gully side walls, while weeds (mainly *Hyptis suaveolens*) had invaded several areas around the rock structures (Figure 55f).

As another illustration using these same gully soils and exotic grass seeds, overburden sub-soil material from an excavation area was spread across a floodplain flat and reseeded with sabi and Indian blue grass at ~50 kg/ha (Figure 56ab). The seed was raked and covered with a thin layer of soil. Despite some initial germination success, overall there was very poor germination and survival on these sub-soils as indicated by continued bare cover after the wet season (Figure 56c). Comparatively, the success was much greater on the patch margins where some of the original non-sodic topsoil remained. After the second wet season, cover remained sparse, despite some additional colonization by stoloniferous grasses and exotic weeds (Figure 56de).

At a West Normanby gully complex, several small areas of raw gully slope were hand sown with small quantities of native seed (black spear, Queensland blue, kangaroo, blady grass) as a qualitative test of the germination and establishment success. Sowing occurred during early February after heavy rainfall that disturbed, softened, and loosened the soil on raw gully slopes and improved moisture conditions. Each native species was sown on different gully slopes adjacent to each other. By April after the wet season, there was little evidence of the germination and establishment of any of these native species, likely due to a combination of factors.

From these observations, it is clear that germinating and establishing exotic or native grass by hand sowing seeds directly on raw gully side walls and headcuts remains problematic due to the poor seed bed and harsh soil conditions, especially due to the nature of hard-setting sodic soils (high sodium and magnesium). It is generally known that there is poor germination success of sown exotic pasture grass seeds in undisturbed native woodlands, with improved results on disturbed soils; but even under ideal prepared seedbed conditions only 10% of viable seeds might germinate (Hopkinson 1993; 2002). The importance of soil disturbance, seed burial depth, soil sodicity and chemistry, nutrients, organic matter, and water infiltration and availability to the germination and establishment success of native and exotic grass will be highlighted further below in Sections 7.6.2.3, 7.13.3 and 7.13.5. Scarifying and disturbing sodic gully slopes prior to grass sowing could provide a better seed bed, in addition to raking soil over the seed and adding mulch. However, direct disturbance of gully banks could exacerbate erosion unless more intensive stabilization intervention is conducted (e.g., battering, adding soil amendments, grade control, Sections 7.13.3 and 7.13.5). Additional quantitative trials are needed to more precisely determine the potential for native or exotic grass seed germination and establishment on raw gully slopes after sowing. Experimentation will be especially needed in the context of revegetating large areas of alluvial gullies with grass seed spread through aerial seeding from plane or helicopter (Section 7.6.6).

a) 22-Dec-11 b) 03-Feb-12

c) 07-Apr-12 d) 13-Jun-12

e) 28-Jan-13 f) 04-Apr-13

Figure 55 A gully that has been hand sown with grass seed (~50 kg/ha *Urochloa mosambicensis and Bothriochloa pertusa*) following installation of grade control structures during a) 22-Dec-11 immediately after seeding and mulch application, b) 03-Feb-12 during wet season growth, c) 07-Apr-12 during wet season growth, d) 13-Jun-12 during the early dry season, e) 28-Jan-13 during the early-wet season and following 400mm of rainfall, and f) 04-Apr-13 after the wet season.

a) b)

c)

d) e)

Figure 56 A site example where grass (~50 kg/ha *Urochloa mosambicensis and Bothriochloa pertusa*) was hand sown on a) gully sub-soils remaining after gully rehabilitation, b) sparse germination success after the first few rains, c) continuing bare cover at the end of the first wet season, d) continued sparse cover after the end of the second wet season, and e) close-up of low density grass cover after two years.

7.6.2.3 Hydromulching of In-Situ Gully Head Scarps and Scalds

Hydromulching raw or eroded surfaces has the distinct advantage of directly applying a suite of physical, chemical and biologically amendments to a raw soil surface to enhance vegetation establishment, all without disturbing the soil surface common to other planting techniques. The hydromulch mix can vary depending on applications, but the mix used for Normanby catchment experiments is listed in Table 5. The cost of this mix commercially delivered and applied was ~ $2 per square meter or $20,000 per ha. It is fairly easy to apply using commercially available contractor equipment that utilises a mobile hose or spray gun. However, reasonable truck access to the site is needed (across floodplain flats), as well as a local water source such as a farm dam within reasonable driving distance (5-10km). The hydromulch can be applied as a Bonded Fibre Matrix (BFM), which is a mat of hydromulch mix sprayed on in layers of varying thicknesses in different directions. Multiple layers and angles of spray provide complete coverage and eliminate 'windowing' into the soils beneath, to minimise water undermining the mat.

Table 5 Hydromulch mix used for revegetating raw gully slopes at Crocodile Station

Amendment	Description	Application Rate
Hulled couch grass	Perennial exotic grass *(Bothriochloa pertusa var. Bowen)*	15 kg/ha
Unhulled couch grass	Perennial exotic grass *(Bothriochloa pertusa var. Bowen)*	15 kg/ha
Sabi grass	Perennial exotic grass *(Urochloa mosambicensis var. Saraji*)	10 kg/ha
Japanese millet grass	Annual exotic grass *(Echinochloa esculenta*)	20 kg/ha
Verano stylo	Perennial exotic herb *(Stylosanthes hamata)*	10 kg/ha
Starter fertiliser	N-P-K = 12-5-14	250 kg/ha
Curosol	Tackifier glue, co-polymer poly-vinyl alcohol	120 litre/ha
Envirotak	Tackifier glue, guar and psyllium gums	30 kg/ha
Paper	Organic amendment and surface cover mulch	1,500 kg/ha
Bagasse	Residual sugar cane fibre	4,500 kg/ha
Gypsum	$CaSO_4$ applied as 50/50 Gypsum/Gypflo	10 tonne/ha

On Crocodile Station in Dec-2011, raw eroded slopes of gully headcuts, side walls and scalded areas were hydromulched as an initial test of the use of vegetation to stabilise gully slopes without the need to regrade or disturb the slopes. The seed/amendment/water mixture (Table 5) was sprayed directly on raw eroded slopes using hoses (Figure 57). In some extreme cases, the complex and crenulated surface area of the gully walls prevented 100% coverage due to extreme shadowing and angling effects, but coverage generally exceeded 80% from multiple angles, which was sufficient for initial testing.


a) b)

Figure 57 Spraying on hydromulch mix (Table 5) to a) raw eroded gully slopes at CRGC1-28, Dec 2011, and b) scalded gully slopes at CRGC62 with lags of ferricrete pebbles. Note hydromulch truck and tank in background, and application hose.

By April 2012, observations of grass establishment on the CRGC1-28 gully scarp suggested that direct hydromulching raw in-situ gully faces was only successful in patches. Sabi grass (Urochloa mosambicensis var. Saraji) had the best establishment success in patches at

CRGC1-28. Establishment success was minimal on steep active faces or on dry convex slopes where soil moisture and retention was least available (Figure 58). Grass survived only in areas where moisture concentrated or was retained, especially on slumped soils in rill and gully hollows, but not in rapidly eroding gully channels (Figure 59).

Due to the remote area and lack of water trucks, the hydromulch was not watered as commercially recommended after application (>8mm per day for the first 10 days). This would not be practical in most gully erosion situations anyway due to remoteness. However in this case due to targeted application at the beginning of the wet season (mid-Dec), several days of follow-up rains (> 20mm/day) helped seeding survival after application (Figure 105). In contrast, two weeks of no rain in early Jan-2012 could have hampered subsequent survival in the driest micro-habitats such as steep faces and convex slopes. It is unknown whether improved vegetation establishment would have occurred on these gully soils during a wetter period, with artificial watering, with more complete hydromulch coverage, and/or by spraying on additional layers to create a thicker BFM.


a) b)

Figure 58 Hydromulch coverage at CRGC1-28 a) just after application in Dec 2011 and b) following germination and wet season growth in April 2012.


a) b)

Figure 59 Hydromulch grass establishment at CRGC1-28 by a) April 2012 and b) April 2013. Note the germination success in hollows and concave slopes, but not in active channels or convex slopes with little moisture. Gray areas represent hydromulch mix that did not germinate due to desiccation on these surfaces.

At another site on Crocodile Station (CRGC62), two adjacent shallow gullies with surface scalding and ferricrete nodules on the surface were used as control (CRGC62b, Plot 511) and treatment (CRGC62a, Plot 507) sites for hydromulching application of raw scalded gully slopes (Figure 60). Before and after photographs indicated that vegetation establishment (both grass and stylo) was best on slopes with some original soil intact (Figure 61b), but especially along the gully floor where water and nutrients concentrated (Figure 60). Establishment was poorest on scalded slopes with lags of ferricrete nodules (Figure 61a). At CRGC62, verano stylo (*Stylosanthes hamata*) dominated on slopes with some original soil intact, compared to completely scalded slopes (Figure 60cd). Vegetation monitoring plots along the valley bottom indicated that hydromulching doubled the cover of live vegetation compared to before/control conditions (Figure 62). However, raw slopes remained at both the control and treatment sites. Indirect/passive vegetation recovery over longer time periods (5-10 yrs) will be monitored in association with stock exclusion at this CRGC62 site (see Section 7.5.2.2; Figure 45).

Other examples of hydromulch applications for battered gully slope stabilization will be provided further below (see Sections 7.13.3 and 7.13.5).

a) b)

c) d)

e) f)

Figure 60 Before and after photos of a) CRGC62a (Plot 507) gully before hydromulch treatment in Dec 2011, b) neighbouring CRGC62b (Plot 511) control gully in Dec 2011, c) CRGC62a (Plot 507) gully after hydromulch treatment in April 2012, d) neighbouring CRGC62b (Plot 511) control gully in April 2012, e) CRGC62a (Plot 507) gully after hydromulch treatment in April 2013, f) neighbouring CRGC62b (Plot 511) control gully in April 2013.

a) b)

Figure 61 Examples of a) poor germination of hydromulch mix on scalded gully slopes with ferricrete and b) modest germination of hydromulch mix on relatively intact soil surfaces.

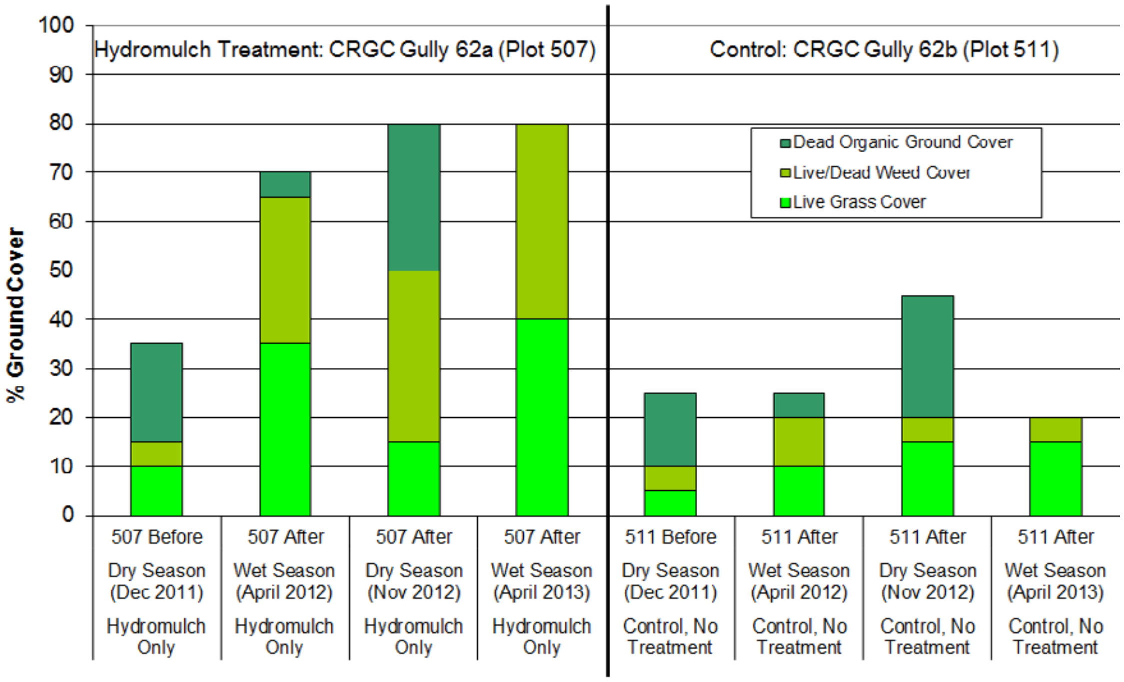


Figure 62 Percent ground cover before (Dec 2011) and after (2012/2013) hydromulching application at control (511) and treatment (507) vegetation plots within CRGC62ab. Vegetation plots were located on the gully floor where establishment was best, in contrast to adjacent scalded slopes with scalding and ferricrete nodules where establishment was poorest.

7.6.3 Blady Grass (*Imperata cylindrica*) For Alluvial Gully Stabilization

A notable native grass species important for erosion control is blady grass (*Imperata cylindrica*). It is a native to the Normanby catchment and Cape York Peninsula (Weston 1988; Neldner et al. 1997) and is common along some of the river banks and gullies of the eastern sections of the Normanby catchment (East and West Normanby Rivers, Normanby mainstem) (Figure 36; Figure 37; Figure 63). In some parts of Cape York Peninsula, *Imperata cylindrica* grasslands are a threatened ecosystem and are culturally valued by aboriginal people (Neldner et al. 1997; Dunlop 2007).

Blady grass has some advantages to controlling erosion around alluvial gullies compared to other native and exotic species. It tolerates low nutrient soils such as sodic alluvium and tolerates disturbance such as fire and erosion. It is generally less palatable to cattle than other pasture species, except for young nutritious shoots emerging just after cutting or fires (Falvey 1981). Therefore cattle in north Queensland generally are not attracted to it and do not over-graze it. However, it is used as cattle forage overseas in Asia, but is generally under-appreciated and under-utilised as a natural resource (Falvey 1981).

Blady grass has deep dense roots, which are excellent for erosion control (Khybri and Mishra 1967). Despite being an invasive weed overseas (e.g., USA), historically it was actively used and planted for erosion control (FAO 2012). It spreads by both rhizomes and wind-blown seeds, can form dense monocultures, but often has spaces or gaps between plants. It is drought tolerant due to its rhizomes. It competes very successfully with exotic weed species. It can be prone to occasional high intensity fires, but these are generally short lived, with perennial shoots resprouting quickly. It is generally spread by the land use actions of man (e.g., inappropriate fire and grazing regimes; Falvey 1981), so therefore is highly suited to mismanaged parts of Cape York Peninsula.

Blady grass seeds are available commercially, but generally not in mass without special order. One of the main disadvantages to blady grass is that it has very small, light, wind-blown seeds. This is good for propagation once established, but this small seed makes it hard to easily sow via conventional methods. However, some newer sowing technologies could overcome this. For example, blady grass could be utilised in a hydromulch mix and sprayed on eroded gully scarps and sidewalls. More optimistically, it could be aerial spread via pellets or other methods from an airplane over eroded and gullied riparian zones.

A small quantity (60g) of blady grass was obtained commercially in early 2013 for qualitative seeding, germination, and growth tests in alluvial gullies in the Normanby catchment. Once the wet season rainfall had set in by February 2013, with follow-up rainfall, small clumps of blady grass seed were hand sown on to gully surfaces as well as ‘finger pushed’ into wet soils of gully scarps and slopes at several gully sites in the Normanby (CRGC1-29-7, GNGC1, West Normanby). Repeat observations and photographs indicated that germination success was extremely poor, with no blady grass growing and surviving into the dry season with identifiable seed heads or plant characteristics. Reasons for poor germination and lack of establishment success are unknown; but it could be due to the viability and age of the seed, the ease of establishing from seed, the harsh nature of the sodic gully soils for seed germination and growth, or the method or timing of sowing or seed placement. Blady grass is easier to establish from rhizomes divided from existing plants (Falvey 1981; Ian Chivers, Native Seeds Ltd., personal communication). However planting via rhizomes by hand places a major limitation on any objectives for broadacre establishment for large-scale gully erosion control. Future efforts and quantitative experiments will be needed to determine the overall viability and best methods for establishing baldy grass in alluvial gullies for erosion control.

Figure 63 Blady grass (*Imperata cylindrica*) growing in and around the rounded and scarp heads of alluvial gullies along the West Normanby River and Normanby River mainstem.

7.6.4 Vetiver Grass (*Chrysopogon zizanioides*) For Alluvial Gully Stabilization

Many gully erosion scientists have recommended using the sterile vetiver grass (*Chrysopogon zizanioides*, cultivar Monto) from Asia, which is perennial, very deep-rooted, non-invasive (generally sterile for the Monto genotype), and generally unpalatable to cattle. It has been used around the world to stabilise soils and slopes in combination with other bioengineering methods (Gray and Sotir 1996; Ndona and Truong; 2005; Mickovski and van Beek 2009; Jolley 2009). The sterile cultivars (Monto) only grow where planted, since it does not generally spread by seed, but rather by asexual offsets (clones). This lack of self-propagation by seed is a major disadvantage in terms of stabilizing >>2000 ha of alluvial gully in the Normanby catchment, which would be very expensive and difficult if this total area was hand planted without positive feedbacks of seed spreading, let alone across >100,000 ha of alluvial gully in northern Australia (Table 1). However, use of vetiver grass for gully stabilization could be important in strategic areas, and should be trialled for alluvial gully control in highly sodic alluvial soils in the Normanby catchment or beyond.

Weed invasion concerns regarding the viability and fertility of vetiver grass seed (cultivar Monto) were investigated for vetiver hedge rows planted by the Queensland Department of Main Roads in the Cook Shire (Hopkinson 2002; Figure 64). While this vetiver grass will produce seed heads (Figure 64), it was found that only 0.0025% (1 in 40,000) seed structures produced viable seed caryopses (Hopkinson 2002). Most of what they produce as apparent seeds is actually 'inert chaff'. Thus the risk of current or future generations of vetiver to spread naturally was deemed extremely low.

Figure 64 Vetiver grass (*Chrysopogon zizanioides*) hedge rows and seed head growing along the Cooktown Highway that was planted for erosion control by the Queensland Department of Main Roads.

7.6.5 Other Native or Exotic Species as Vegetation Erosion Control in Alluvial Gullies

The issue still remains of how to best stabilise alluvial gullies with vegetation to reduce erosion, and especially of determining what species will actually grow and prosper in sodic silt and clay soils with low nutrients, low organic matter, and low water availability? Through discussions with graziers, land managers, road crews, scientists, and laymen regarding alluvial gully stabilization, the idea and question of using an exotic or native 'super plant' to stabilise alluvial gullies had consistently come up. A 'super-plant' for this purpose might or might not exist depending on inherent physical and biological constraints, economic costs, and cultural and environmental values.

For example, sterile vetiver grass (*Chrysopogon zizanioides*, cultivar Monto) is excellent for erosion control, but is labour intensive to plant by clone offsets and will not spread naturally over time. The research trials presented in this report have focused on both self-propagating native grasses appropriate for the region (*Themeda triandra; Heteropogon contortus; Dichanthium sericeum; Imperata cylindrica*), and self-propagating exotic grasses that are highly naturalised in the region and permanent fixtures of the landscape (e.g., *Bothriochloa pertusa; Urochloa mosambicensis*). Utilizing these already existing native or naturalised grasses that are widespread reduces the potential to have unintended consequences of spreading highly invasive weed species.

Northern Australia and Australia as a whole have been a test bed for introduced pasture species (Gramshaw and Walker 1988; Walker and Weston 1990; Cook and Dias 2006) that have had both economic benefits (Clements and Henzell 2010) and severe environmental impacts (e.g., Lonsdale 1994; Mitchell and Hardwick 1995; Noble et al. 2000). Many species were deliberately introduced specifically for soil erosion control, with both beneficial and detrimental consequences (Cook and Dias 2006). Any future interest or research into using exotic grasses and plants for stabilizing alluvial gullies would need to carefully balance any real or perceived erosion control benefits with the true environmental costs of weed invasion.

Many locals in the Normanby catchment have suggested a variety of grasses and plants they think could stabilise gullies, some of which are invasive weeds. These partially include: native blady grass (*Imperata cylindrica*), native Ectrosia grass (*Ectrosia blakei; E. nervilemma E. leporina*), exotic grader grass (*Themeda quadrivalvis*), wynn cassia (*Chamaecrista rotundifolia*), stylo (*Stylosanthes spp.*), and even the dreaded gamba grass (*Andropogon gayanus*). Blady grass is a promising native that is deep root and useful for erosion control (Section 7.6.3). Ectrosia grass species are prolific seeders and commonly colonise disturbed areas such as road sides and sandy drains (Keith McDonald, personal communication). They have been observed in and around alluvial gullies (Appendix 10.6), but their ability to stabilise and proliferate in sodic gullies is unknown. Annual exotic grader grass is found growing in and around alluvial gullies, but generally not in dense swards in gullies and without deep roots that could stabilise sub-soils; however mats of dead grader grass can provide decent protection from rainfall impacts in the early-wet season if it is not burnt. Wynn cassia often grows as dense cover on floodplain terraces where introduced, but does not grow well on sub-soils in gullies. It can provide good cover, but has modest root cohesion, competes with desired 4P perennial grasses, and can accelerate erosion in native pastures (Noble et al. 2000; O'Gara 2005). Species of Stylosanthes have been observed to grow in some rounded alluvial gullies (Figure 36), but generally do not colonise well on the sodic sub-soils of extremely active alluvial gullies.

No observations of highly invasive and ecosystem transforming grasses such as gamba grass (*Andropogon gayanus*) have been made in alluvial gullies in riparian zones on Cape York Peninsula, since strict quarantine procedures are in place for their control. Some positive but mostly negative experiences from these transformer species in the Northern Territory may be informative in terms trade-offs between ecosystem impacts and erosion control. Furthering the spread of species such as gamba grass on Cape York Peninsula would be detrimental to native ecosystems despite its ability to thrive in low nutrient soils and tolerate drought and fire. For example, gamba grass tends to best colonise riparian river margins and flats in northern savanna ecosystems (Petty et al. 2012), where alluvial gullies concentrate, but its downstream colonization along creeks and rivers could fundamentally transform riparian and aquatic ecosystems (e.g., Rinyirru (Lakefield) National Park).

Extreme caution will be needed if considering the use of exotic species to stabilise alluvial gullies, in order to avoid any unintended consequences or severe environmental impacts of weed invasion on northern Australian savanna, riparian and wetland ecosystems.

7.6.6 Potential for Aerial Seeding Alluvial Gullies for Rehabilitation

Due to the large scale and wide distribution of alluvial gullies across the Normanby catchment and northern Australia (Figure 14; Figure 18; Table 1), rehabilitating eroded gullies and adjacent floodplains/terraces with vegetation will require large-scale efforts. Stabilizing one gully at a time is not very practical or economical for cumulative sediment reduction purposes, and is more suitably conducted for local protection of assets (roads, yards, key paddocks, cultural sites). Therefore, rehabilitation efforts and actions should be focused on large concentrated areas of gully erosion to cumulatively reduce sediment yields at the sub-catchment scale.

Broadcast aerial seeding from aircraft of suitable and desirable grass or plant species could be a key mechanism to improve vegetative cover and reduce erosion in and around alluvial gullies at a large scale. Aerial seeding could be complemented by other large-scale land management actions to prevent or reduce alluvial gully erosion, such as spelling or excluding cattle from large erosion sensitive areas, instating alternative or traditional fires regimes (low intensity winter burns), controlling weeds, and improved road management (Section 6.5).

Aerial seeding of pasture species (exotic and native) has been used to “improve” or rehabilitate pastures in Australia since the 1950s (e.g., Campbell 1992; Shaw and Tincknell 1993). However, aerial seeding into existing grasslands in northern Australia has had mixed results (Shaw and Tincknell 1993; Cook et al. 1993), and no documented studies have been attempted to aerial seed grass into alluvial gullies along degraded river margins and river frontage. The poor germination success of sown exotic pasture grass seeds in undisturbed native woodlands is well known (Shaw and Tincknell 1993; Cook et al. 1993; Hopkinson 2002), but improved results can occur on disturbed soils (Hopkinson 2002). However even under prepared seedbed conditions, > 90% of viable seeds often fail to germinate (Hopkinson 1993; 2002).

Species choice, preparation, and methods of aerial seeding would need careful consideration for aerial seeding. The potential ecosystem impact from invasive species is a fundamental consideration (Section 7.6.4 above). The use of native grasses that originally stabilised river frontage margins is preferable (e.g., *Themeda triandra; Heteropogon contortus; Imperata cylindrica*). However, monetary costs of native seeds, weed control, and subsequent grazing impacts need to be considered, such as excluding cattle from seeded areas for many years to promote establishment. Other more practical considerations also need to be taken into account, such as species habitat requirements, method of spreading seed, timing of seed spreading, and the potential for germination and establishment success. Some chaffy or irregularly shaped seeds need to be mechanically processed and/or coated for ease of broadcast seeding from land or air (Loch 1993). Coating seeds with pesticides can minimise the loss of seed to ants (Campbell 1982). Seed viability and dormancy are also important issues (Hopkinson 1993). For aerially spreading seed into alluvial gullies, both airplanes and helicopters could be utilised. Helicopters have the advantage of more targeted seed spreading in gully complexes, while airplanes can carry heavy loads and cover larger areas.

The timing of aerial seed spread is critical in relation to soil moisture, germination, and establishment success, such as >35 mm of rain over 3 days for germination and > 25 mm per week for 4 weeks for establishment (Shaw and Tincknell 1993). Soil moisture and availability to the full circumference of each seed is critical. Soils with low moisture penetration and retention, under tropical conditions with high evaporation and soil drying in the early summer, provide harsh locations for seed germination and establishment (Hopkinson 1993; Cook et al. 1993). This would be the case for hard-setting sodic soils in alluvial gullies (Sections 7.6.2.2; 7.6.2.3; 7.13.5). Therefore where possible, it is important to cover seed with soil or mulch for moisture retention, but this would be impractical when aerial seeding alluvial gullies in the wet season.

Aerial seeding alluvial gullies *after* heavy soaking rains in the early-mid wet season could be an optimal alternative, as sown seeds would benefit from 1) loosened soils via moisture penetration and fresh erosion of slump blocks, 2) increased microsite availability in freshly eroded soils, and 3) increased soil moisture availability. However, follow-up rains over the following weeks would also be essential for germination and establishment success to avoid seed desiccation in hard-setting sodic soils. The use of modern weather and short-term climate forecasts (Bureau of Meteorology) will be essential to predict optimal aerial seeding timing. During the driest years with below average rainfall, aerial seeding might not be viable or economical in tropical savannas and alluvial gullies. The requirement for such particular conditions would be a problem for the typical government 2-4 year natural resource management funding cycles, where the money typically has to be spent in an allotted timeframe regardless of whether it is appropriate.

Experimentation in aerial seeding alluvial gullies during the wet season with a variety of plant species is needed before larger scale programs could be developed to address cumulative erosion impacts at the catchment scale.

7.7 Organic Soil Amendments

7.7.1 Literature Review

7.7.1.1 Surface Mulch Amendments

In agricultural settings, soil surface cover from crop residue and mulch following no-tillage agriculture can significantly increase soil water retention and reduce soil erosion compared to conventional tillage (Thomas et al. 2007; Triplett and Dick 2008). No-tillage soils with cover from crop residue have significantly lower soil erodibility coefficients (Kc) than conventionally-tilled or reduced-tilled soils (Knapen et al. 2007). Much of the reduction in soil erosion can be explained from reduced physical soil disturbance and increased surface cover protecting unvegetated soils from rainfall kinetic energy, aggregate breakdown, and seal formation. Secondary benefits come from increased infiltration and deep drainage, increased surface roughness, decreased runoff velocity and volume, and increased soil organic carbon (see below) (Thomas et al. 2007).

In non-agricultural settings, surface cover from plant residues, mulch, and compost is similarly important in reducing soil erosion and increasing soil water retention. Management actions can either promote the retention of plant organic matter on the soil surface (see above), or actively (re)introduce organic mulches to soil surfaces to reduce future erosion. The latter is one of the most common soil erosion reduction techniques for exposed or denuded soils, while the former is the most sustainable. Direct mulch application is now common place at construction sites (Gray and Sotir 1996; Faucette et al. 2005; McLaughlin and Brown 2006; NRCS 1992), in areas burned by fire (Robichaud et al. 2010), and at river bank revegetation projects (Rutherfurd et al. 2000; NRCS 2007c). Often mulches are used in combination with grass seeding or tree planting to improve germination conditions such as retaining moisture, protecting seeds from down slope wash, and inhibiting weed growth and competition.

Dry loose mulches include local mulches of natural grass or forest debris (leaves, stems, woodchips), introduced agricultural straw (wheat, barley, rice, etc.), introduced wood mulch (chips, shreds, strands), and various types of compost. They can be applied by hand or mechanically using blowers or dropped from helicopters (Robichaud et al. 2010). They are often spread in combination with plant seeding. Caution should be used to obtain “weed-free” mulches, as weeds associated with some straw mulches can have unintended consequences once established at rehabilitation sites (Beyers 2004; Kruse et al. 2004). Depending on application rate and depth, they can also have unintended consequences of inhibiting the emergence of seedlings through the mulch (Robichaud et al. 2010).

Geotextile fabrics of various types (straw, coconut, jute, etc.) and erosion control blankets (organic material interwoven into a mesh) have been extensively used at construction sites and streambank stabilization projects over the last few decades (Gray and Sotir 1996; NRCS 2007c). These blankets and fabrics can be rolled out onto soil surfaces and tacked to retain cover in place compared to other loose dry mulches. Their performance at erosion control varies (Faucette et al. 2009a), but they are most often used with other techniques such as grass seeding or tree planting.

Compost blankets have been increasingly used for erosion control in the last decade. These "blankets" are actually surface covers of certified quality compost applied to standard depths. Compost can be applied via manure spreaders or pneumatic blowers that deliver it to the soil surface. Seed or other soil amendments like polyacrylamide (PAM) or gypsum can also be delivered to the soil surfaces with the compost when using pneumatic blowers. Compost blankets and mixtures of compost with other soil amendments have been shown to be highly effective at erosion control, typically exceeding the performance of other standard techniques in isolation or combination (Faucette et al. 2005; 2007; 2009a).

Wet mulches (a.k.a. hydromulch) include mixtures of water and mulch that can be sprayed onto soil surfaces (see Section 7.6.2.3, 7.12.3 and 7.12.4). They often include mixtures of grass or other seeds (a.k.a. hydroseed), and soil binding agents (tackifiers) of either organic (polysaccharides from plants) or synthetic (polymers such as PAM, see below) form. They can be mixed on site in large truck mounted tanks using local and imported dry ingredients (seed, mulch, fertiliser, tackifiers, etc.). Since hydromulch mixes stick to soil surfaces, they generally stay in place and are resistant to water and wind erosion. Compared to dry mulches and compost, they do not roughen the soil surface and thus are less effective at resisting overland flow. However, the mulch and tackifier bind the soil together and resist erosion during initial rainfall, making hydromulch an effective short-term erosion control agent. Hydromulch components break down more quickly than dry mulches and compost, resulting in less soil protection over time. However, the establishment of grass as a result of hydroseeding can progressively take over the role of soil protection and binding (see Sections 7.6.2.3, 7.12.3 and 7.12.4).

In landscapes naturally prone to fire such as tropical savannas, the generation and protection of natural surface mulches of organic detritus is intricately linked to the proactive management of the fire regime. Fire breaks, season of fire use, intensity of fire, and annual frequency of fire could all be important factors in creating or retaining surface mulches and organic carbon. The retention of applied surface mulches such as straw for rehabilitation will also be affected by fire potential, and thus should be managed cautiously.

7.7.1.2 Soil Organic Matter Amendments

Soil organic carbon (SOC) (living and dead) within a soil profile is important in maintaining soil structure and reducing soil erodibility. SOC can help cement soil particles into stable aggregates, increase biological activity, and increase the porosity and permeability of soils (Tisdall and Oades 1982; Carter and Stewart 1995). Biological activity associated with SOC can transform organic material into polysaccharides and other natural polymers that bind soil particles into aggregates important for stability in sodic soils, similar to synthetic polymers (see below) (Sumner 1995).

For sodic soils that have a tendency to slake as well as disperse, increasing SOC can significantly decrease soil slaking (Chan and Mullins 1994), likely due to both increased aggregate strength and reduced wetting rates. Slaking is the process of soil aggregate fragmentation under rapid wetting when matrix suction is at its maximum. However, Rengasamy and Olsson (1991) state that while SOC can help reduce slaking, it will not help with reducing dispersion until Na^+ is first replaced with Ca^{+2} to stabilise aggregates.

The amendment of agricultural soils with organic matter or compost is common for soil fertilization and structural improvement. Modern applications of organic matter to a variety of soil types and uses have moved beyond just livestock wastes (manure) and by-products (meat, blood and bone meal) to include compost, compost tea, vermicasts, fish hydrolysates, seaweed extracts, biochars, biosolids (sewage sludge), paper industry wastes (pulp), cheese whey, and other industry and agricultural waste products (Graber et al. 2006; Quilty and Cattle 2011). Many of these organic soil amendments have been found to be beneficial to aggregate stability and soil structure in agricultural settings (Graber et al. 2006). Compost blankets for surface soil protection, erosion reduction and organic matter amendment also have become increasingly popular and effective (Faucette et al. 2005; 2007; 2009a). The application of compost and soil organic matter to protect, stabilise, and fertilise soils in other settings such as rangelands degraded by gullies has been limited.

Overall, the importance of SOC to the stability of soils highlights the necessity for the progressive management of surface vegetation communities in maintaining pools of carbon available for incorporation into the soil profile. This could be especially true in savanna rangelands where SOC can dominate total carbon stocks (Chen et al. 2003) and below-ground SOC is influenced by the above-ground dynamics of grasslands, overstorey woodlands, and land use such as grazing and fire management (Chen et al. 2005). Since SOC typically decreases with depth in highly inorganic soils, the influence of SOC is likely most important for soil surface processes influencing erosion such as infiltration, surface sealing, scaling, runoff depth, surface soil erosion resistance, and gully erosion initiation.

Along river frontage country in tropical savanna rangelands, there are likely multiple environmental, social, and economic benefits to increasing SOC stocks through proactive land management (e.g., grazing and fire regimes). Local increases in SOC will benefit soil hydrological functions and erosion resistance. Increases in SOC will also promote soil biodiversity (i.e., microorganisms) that will in turn benefit soil stability. Cumulative increases in SOC at the sub-catchment scale will have the combined benefit of sequestering carbon at the landscape and global scale as well as reducing gully erosion that threatens soil integrity and carbon stores, especially if concentrated areas of soils prone to alluvial gully erosion are targeted. The growing carbon market (i.e., carbon farming) could be and effective mechanism to help pay for land management actions that in combination increase soil organic matter and reduce gully erosion.

7.7.1.3 Bacteria Soil Amendments

Bacteria and other soil microorganisms (fungi, actinomycetes, algae, protozoa) are important regulators of soil chemistry and stability. Reclamation of sodic soils has increasingly utilised soil bacteria combined with organic matter amendments to reduce exchangeable sodium and high pH values. Bacteria effectively break down organic matter into a variety of useful substances such as macro-and micro nutrients, organic acids, sugars, polysaccharides, and soil humus, which are beneficial to plant growth and soil stability. For example, the stimulation of bacterial growth in sodic soils with organic matter amendments can decrease the soil pH from organic acids, release calcium stored previously in unavailable forms, replace exchangeable sodium with calcium, and thus reduce soil dispersion and increase water infiltration (Odell 2000; Sahina et al. 2011). Soil bacteria also can release polysaccharides through the decomposition of organic residues, which promotes soil aggregate stability, hydrological functions, and erosion resistance (Ashraf et al. 2013; Singh and Dhar 2010). This bacterial benefit would be in addition to the more direct benefits of adding just organic matter to soils to improve structure, stability, and the organic complexing (binding) of salts in soil (Section 7.7.1).

The use of cyanobacteria for sodic soil reclamation is most promising, as cyanobacteria have evolved over billions of years to tolerate inhospitable environments with high salt contents and high pH. Singh and Dhar (2010) review the potential for sodic soil reclamation with cyanobacteria. Cyanobacteria can produce polysaccharides that promote aggregate formation, enrich the soil with fixed nitrogen, and even scavenge (uptake) sodium cations from the soil during the nitrogen fixing process (Singh and Dhar 2010). For sodic soil reclamation, cyanobacteria are most often added in junction with gypsum and organic material amendments, otherwise these materials can also be used to bolster existing populations of cyanobacteria in the soil.

The use of compost and compost tea (brewed liquid extract of compost) has become a common method to add beneficial soil bacteria and other microorganisms to the soil, as well as improve nutrient retention and uptake in soils (Ingham 2005). It is commonly used in organic agriculture, but may also have applications to sodic soil reclamation over rangelands if the benefits can be realised at a large scale. However, the tea only extracts what life is in the compost, so compost creation and selection need to take into account the desired and supplemented species for soil reclamation (Naidu et al. 2010), especially in relation to infertile sodic soils in rangelands.

7.7.2 Normanby Catchment Examples

In the Normanby catchment, the use of organic compost, dry straw (hay), and hydromulch to protect the soil surface and amend the soil with nutrients, carbon, and bacteria was conducted at the plot scale in gullies at Crocodile Station (see Sections 7.6.2.3, 7.13.3 and 7.13.5).

7.8 Chemical Soil Amendments

7.8.1 Literature Review

Sodic soils with high levels of exchangeable sodium suffer from physical degradation of the soil structure due to enhanced swelling and aggregate dispersion upon wetting. Sodic soils are prone to erosion from sheet wash, rilling, and gullying due to lack of structural and aggregate stability. They can also suffer from low fertility. The soil types, chemistry, and physical structure associated with sodic soils are complex both spatially and temporally diverse across Australia and the world (Naidu et al. 1995). Despite this diversity, there are several common chemical methods for ameliorating sodic soils in both agricultural and rangeland settings.

7.8.1.1 Gypsum

Gypsum ($CaSO_4$) is the most common soil amendment for rehabilitating sodic and hard-setting soils in agricultural soils (Sumner 1995; Keren 1996; Mullins 1998; Graber et al. 2006) and dryland pasture soils subject to gully erosion or scalding (Jones 1969; Muirhead 1974; Floyd 1974; Boucher 1990; Boucher 1995). Reduced clay swelling and dispersion is accomplished by replacing exchangeable sodium (Na^+) with calcium (Ca^{+2}) on clay particle exchange sites (cation-exchange effect) and increasing the concentration of cations in surface water when high quality rainwater predominates (electrolyte effect). Typically the use of small gypsum particle sizes is preferred due to more rapid solubility, such as with the use of fine grained 'by-product gypsum' (phosphogypsum from phosphoric acid creation) being preferred over 'mined-gypsum' (Levy 1996; Graber et al. 2006). Lime ($CaCO_3$) and calcium chloride ($CaCl_2$) can also be used, but lime is less soluble than gypsum and calcium chloride is more expensive.

Gypsum can have long- or short-term beneficial effects to the structure and chemistry of sodic soils, depending on the rate of application, surface or sub-surface application, soil type, and the soil properties such as the exchangeable sodium percentage (ESP) and concentration of electrolytes in the surface soil. When gypsum is mechanically broadcast onto soil surfaces with low electrolyte concentrations under natural rainfall conditions, both the cation-exchange effect but especially the electrolyte effect, are important in reducing swelling, dispersion, crust formation and soil surface sealing, which increase soil permeability, (not porosity), hydraulic conductivity and field infiltration rates of surface rainwater (Keren 1996; Graber et al. 2006). Surface application also partially protects the soil (mulch-effect) from direct rainfall impacts and mechanically inhibits seal formation. Overall these surface effects of gypsum decrease surface soil erosion by 1) increasing infiltration and decreasing runoff depths, 2) increasing aggregate stability and decreasing soil detachment, 3) increasing surface roughness, decreasing velocity, and 4) increasing suspended clay flocculation and deposition (Levy 1996; Graber et al. 2006). However the electrolyte effect on reduced soil dispersion and erosion can be short lived if high-quality rainwater continuously flushes electrolytes from the soil surface deeper into the soil profile or down slope on a soil surface.

The cation-exchange effect is more important for prolonged changes in soil chemistry and structural stability (Keren 1983; Sumner 1995; Keren 1996), especially if high ESP values are found throughout the profile. This might be especially important if the stability and dispersibility of sub-soils is influencing the propagation of gully head scarps. If soils are highly sodic at depth and leading to enhanced gully erosion, sub-surface application may be important through deep ripping (ploughing) of the soil and gypsum application throughout the tilled layer (Jayawardone and Chan 1995). However, if sub-surface soils are dramatically more sodic than surface soils, deep ripping may not be desirable to avoid bringing these sodic soils to the surface.

The gypsum application rate depends on the area and volume of soil to be treated, the existing soil ESP values, and the future target ESP values that will promote soil stability. Typical surface application rates on agricultural soils are between 3 to 6 t ha^{-1}, up to 15 t ha^{-1} (Jayawardone and Chan 1995; Boucher 1995; Sumner 1995). Minimum surface application rates of ~ 2 t ha^{-1} are needed to assist re-establishment of vegetative grass cover (Boucher 1995). Rates higher than 10 to 15 t ha^{-1} will be needed to reduce sub-soil sodicity (Floyd 1974; Jayawardone and Chan 1995; Boucher 1995). For extremely sodic soils with high ESP values (>50%), maximum application rates can exceed 80t/ha (Naidu et al. 1995; Nelson et al. 2000; Coventry 2004)(see Section 7.13.3 and 7.13.5). Several methods are available to calculate the gypsum requirements of soils depending on chemical and physical characteristics and desired level of treatment (Keren 1996; Nelson et al. 2000; Suarez 2001; Coventry 2004).

7.8.1.2 Synthetic Polymers

Synthetic organic polymers can be used in sodic soil as conditioners to improve aggregate stability, reduce surface seal formation, increase infiltration rates, and reduce runoff and erosion (Levy 1996; Graber et al. 2006; Ben-Hur 2006; Sojka et al. 2007). Polyacrylamide (PAM) and polysaccharide (PSD) are the two most commonly used and researched synthetic polymers for soil conditioning, although many formulations of these exist. They are typically applied in solution form just to the soil surface where they are absorbed onto clay particles or the surface of aggregates, reducing repulsive forces and dispersion. They also can be applied in granular form due to solubility issues, however with mixed results (Graber et al. 2006). Polymer application can also be supplemented with gypsum with additive effects, especially under high kinetic-energy rainfall events that break down surface aggregates and promote seal formation (Levy 1996; Ben-Hur 2006).

Soil stabilizing polymers have been most often used in irrigated agriculture for promoting infiltration and reducing erosion. However polymers (especially PAM) are increasingly being used for erosion control in non-agricultural and dryland settings. For example, polymers are being used to reduce erosion and soil loss from construction sites (Hayes et al. 2005), mine waste areas (Vacher et al. 2003), roads and road embankments (McLaughlin and Brown 2006; McLaughlin et al. 2009), landfills (Flanagan et al. 2002), and following rangeland or forest fires (Robichaud et al. 2010). Often PAM is used in combination with other soil stabilization treatments, such as gypsum, mulches, grass seeding, and grade-control structures. PAM can be combined into hydromulch or hydroseed mixtures and sprayed onto soil surfaces by truck-mounted sprayers or even helicopters (e.g., Robichaud et al. 2010). However the use of a mixture of stabilisers makes it hard to isolate the cause and effect of individual components. Some erosion studies have found that PAM was partially ineffectual in isolation (Hayes et al. 2005), while others clearly showed reduced soil loss from isolated

PAM application (Flanagan et al. 2002). Most frequently there are added benefits to including PAM into erosion control treatments (Zhang et al. 1998; McLaughlin and Brown 2006; Faucette et al. 2007; McLaughlin et al. 2009). When included in hydroseed mixtures, the short-term benefits of PAM in increasing infiltration and reducing runoff can increase grass establishment and growth (Flanagan et al. 2002), which in turn promotes longer-term soil stabilization.

The application of synthetic polymers such as PAM for prevention or reduction of deep gully erosion has not been thoroughly researched. Since polymers are most often used on soil surfaces to reduce sheet-flow and shallow-rill erosion, their application to gully control would be under situations where the reduction of the initiation of gullying was desirable, or where existing gully systems were regraded via ripping and sculpting and the new bare surfaces needed stabilization. Potential water contamination issues would also need to be researched before synthetic polymers were utilised in alluvial gullies along river frontages and riparian zones adjacent to water bodies.

7.8.1.3 Fertilisers

Most sub-surface soils that gullies erode into are low in fertility and nutrients, such as sodic soils or C horizons of saprolite. Several gully rehabilitation trials have incorporated inorganic fertilisers into treatments as a tool to boost soil fertility and enhance the establishment of native vegetation. In south-eastern Australian, Boucher (1995) recommended a mixture of superphosphate and lime to aid revegetation of gully (tunnel) erosion following deep ripping or land regrading. Alternatively a mixture of superphosphate and phosphogypsum could be used, both created during similar industrial processes.

In the south-eastern United States, Law and Hansen (2004) describe the successful use of fertiliser application to increase the regeneration success of native plants in and around eroding gullies. They applied 0.4 tonnes/ha of slow release fertiliser (35-17-0) at US$250 per ha during the growing season to eroded gullies recently planted with native vegetation. In heavily degraded area they recommended multiple treatments as dictated by active monitoring on soil conditions. In another gully erosion control study in Nepal, Higaki et al. (2005) found that the application of a compost fertiliser to crusted, nutrient poor, lateritic soil on an alluvial terrace aided in the stabilization of gullied surfaces and germination of grasses.

7.8.2 Normanby Examples

In the Normanby catchment, the use of both gypsum ($CaSO_4$) and fertiliser to amend sodic soils and improve vegetation growth was conducted at the plot scale in gullies at Crocodile Station (see Sections 7.6.2.3, 7.13.3 and 7.13.5).

7.9 Physical Tillage of Gullies on Cleared Agricultural Land

7.9.1 Literature Review

Tillage is the mechanical digging and overturning of the soil surface using human hand, animal, or machine power. For small, shallow, “ephemeral” gullies often in agricultural settings, it is conventional practice for farmers to machine plough or till through gully channels with machinery and continue cropping that land area (Poesen et al. 2003). However, ephemeral gullies often reform in the same general topographic location during subsequent runoff events creating chronic soil loss (Poesen et al. 2003). This is especially true where conventional tillage leads to exposed soils prone to erosion, compared to no-tillage agriculture that retains crop residue and mulch, increases soil water retention, and reduces soil erosion (Thomas et al. 2007; Triplett and Dick 2008). The more progressive use of permanent vegetation buffer strips or grass waterways along these preferential gully pathways has been proven to be effective at reducing sediment loss (Stannard 1977; Pinkerton and Greentree 1991; Poesen et al. 2003; QDERM 2004c).

In Australian tropical rangelands, tillage using chisel and disk ploughs and rippers has been used along with direct grass seeding to rehabilitate bare eroded plains and the shallow upper extents of gully systems (Hudson 1987; Tongway and Ludwig 2002; Payne et al. 2004; Jolley 2009). While successful at improving both exotic and native vegetation cover on the eroded plains (Payne et al. 2004), the influence of these measures on revegetating and reducing gully erosion were unclear but likely minimal (Wasson et al. 2002).

In south-eastern Australia where tunnel erosion (sub-surface gullying) is a common response to land-use disturbance, deep tillage and ripping has been used to break up tunnels (Floyd 1974; Boucher 1990; Boucher 1995). However the physical benefits of reducing tunnel connectivity and increasing vertical water infiltration are often short-lived. Successful long-term rehabilitation depends on the establishment of vigorous vegetative cover (grass and trees) and control of grazing and feral animals following initial tillage. Chemical amendments have also been helpful (Floyd 1974; Boucher 1990; Boucher 1995).

For Australian sodic and hard-setting soils in both agricultural and rangeland contexts, tillage has been used as a physical mechanism to loosen the soil, reduce bulk density, increase macro-porosity, improve soil hydraulic conductivity, and reduce runoff (Jones 1969; Muirhead 1974; Cunningham 1974; Jayawardone and Chan 1995). These structural improvements are usually short-lived in sodic soils depending on future management, unless soil amendments such as gypsum are used, vegetation is used to protect the soil surface from structural decay, and/or organic matter is used to improve aggregate stability. For improvement of sodic soils to greater depths, deep ripping and ploughing to >0.5m has been used along with chemical amelioration with gypsum (Jayawardone and Chan 1995).

7.9.2 Normanby Examples

Few documented examples exist in the Normanby catchment or northern Australia of physical tillage of gullies on agricultural land; however it is likely common in more erodible soils. The Lakeland agricultural district in the Normanby catchment is dominated by deep friable soils derived from basalt (red Ferrosol), and to a lesser extent brown Ferrosols and black Vertosols (Grundy and Heiner 1994). These soils are not readily prone to major gully erosion unless mismanaged or cut by farm roads, fences or deep furrows. Where shallow swales, hollows and other drainage lines have been cleared for agriculture, permanent vegetation buffer strips or grass waterways should be installed to minimise gully erosion potential (Stannard 1977; Pinkerton and Greentree 1991; Poesen et al. 2003; QDERM 2004c). Grade control structures using locally abundant basalt boulders can also be used to reduce gullying into drainage lines on these agricultural fields (Figure 73; Section 7.11.2). However, installation designs must ensure that rock structures are embedded into the bed and banks of drainage lines with a mixture of rock sizes to ensure they are not outflanked by erosion (Figure 73f) or allow water to pipe through large pores of boulders.

Shallow to deep gully erosion on cleared agricultural land is more common on the poorer soils on the margins of the Lakeland district, in addition to silty alluvial soils (sodic and non-sodic) on the cleared terraces of the East and West Normanby Rivers and the middle Laura River. These areas were originally cleared of trees for improved pasture, often accelerating alluvial gully erosion on creek margins and where bulldozers and chains traversed drainage lines during chaining and clearing (Section 7.16; Figure 149; Figure 150). Future agricultural development (tilled pasture, bananas, leucaena, etc.) on these soils could exacerbate soil disturbance and water runoff and accelerate alluvial gully erosion.

On these more erodible soils, it is recommended to install grass and tree buffers (+50 m wide) around creeks, drainage lines, hollows, and breaks in slope to reduce the potential for gully initiation or propagation. Attempting to till or bulldoze shallow gullies (e.g., Figure 149) is not recommended, unless a full suite of treatments, soil amendments, and vegetation plantings are applied to the gully network along with a permanent vegetation buffer (Section 7.13). Installing contour berms could be appropriate on cleared paddocks and fields (e.g., Figure 85), as long as the surface water runoff is managed appropriately and not diverted to steep creek banks and drainage lines where it could fuel more gully erosion. Additionally, earthen berms or banks could be installed above gully heads to divert excess water runoff from cleared fields. But again, the diversion point needs to be selected and designed to not accelerate gully erosion (Section 7.12; Figure 87; Figure 88).

7.10 Physical Armouring At Gully Head Scarps

7.10.1 Literature Review

Structural control of gully head scarps (headcuts) is often the most instinctual reaction to severe gully erosion. “If it is eroding right there, let’s do something right there”. Similar to many other physical treatments to gully erosion, *head scarp armouring treats symptoms rather than addressing the cause of erosion.* However, if designed and engineered correctly for the right soil type and hydrogeomorphic environment, armouring can provide short-term or long-term gains in soil erosion reduction, but sometimes at a monetary and potentially environmental/geomorphic cost.

One of the first instincts of famers and land managers is to place obstructions at the headcut in attempts to protect the soil surface, dissipate energy, or slow retreat via armouring. At first, anything and everything is tried. Old tyres, old cars, old rubble, old fencing wire and scrap metal, and occasionally dead stock add to the mix from falling over the escarpment. Most often these structures do not work due to their ad hoc, patchy application and their failure to address the mechanism for headcut retreat. In dispersive or sodic soils where scarps are driven by both direct rainfall-runoff and sub-surface water seepage out if the scarp face, the structural failure of the soil at the soil aggregate level will promote erosion right around or through these temporary obstructions. In the worst case scenario these rubbish items can redirect water and hasten the erosion, or in the case of old tyres, their slow chemical breakdown can lead to chemical leaching and the pollution of the environment (Fitzpatrick et al. 2005).

a) b)

Figure 65 Old tyres are <u>not</u> an effective measure to reduce gully erosion, can accelerate erosion from water turbulence around tyres, and can add toxic material to soils and waterways from the photo-chemical breakdown of the tyres over time.

Figure 66 Filling gullies in with debris and trash does not reduce erosion and pollutes waterways.

As the next step up in the intensity of intervention, angular rock (rip-rap) is often used to armour gully headcuts and scarps. Designs vary from simple dumping of rock and occasionally backfilling (Figure 67) to intricately engineered structures using a combination of rock, gabion baskets, concrete and vegetation for slope stabilization (Gray and Sotir 1996). However, in silt/clay soils with high levels of exchangeable sodium driving dispersion, large angular rock can be ineffective at holding headcuts and soil in place due to soil dispersion and sediment suspensions moving around or through the rock pores, especially when subject to water runoff from upslope (Figure 68). For hillslope gullies in semi-confined valleys, excavation down to bedrock or more stable soil and backfilling with rock can be effective. In dispersive soils, water cut-off trenches might need to be installed at depth to prevent outflanking of any structural control.

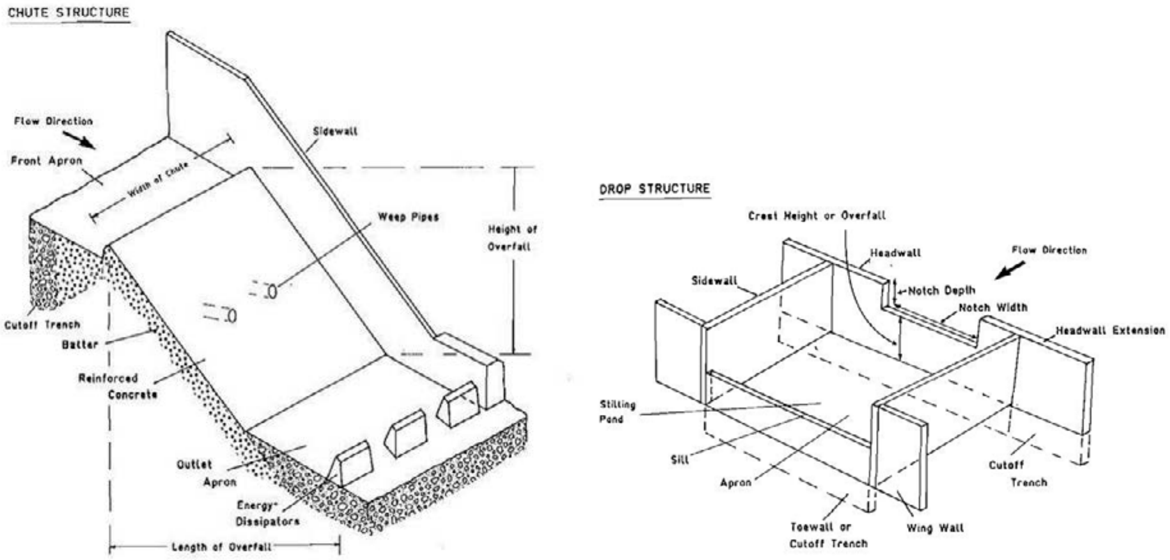
The more classic style of sequentially-stepped grade control structures used over long channel lengths in semi-confined channels will be addressed in Section 7.11.

Figure 67 Angular rock armouring and soil backfill at a gully headcut. Note good kangaroo grass (*Themeda triandra*) and black spear grass (*Heteropogon contortus*) establishment on the soil backfill.

Figure 68 Example of an alluvial gully headcut armoured with angular rock, where seepage and overland flow in dispersive soil has eroded around the rock and continued to propagate upstream, leaving a pile of rock behind as a semi-functional grade control structure.

In Australia, engineered structures have been used for the stabilization of gully headcuts (via grade control and water energy dissipation) in semi-confined hillslope gullies and to safely route overland water runoff over a headcut location (Crothers et al. 1990; Bartlett 1991; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008). Several structural derivatives exist including weirs, chutes, flumes, and drop structures. They are only applicable where surface overland flow dominates erosion and hillslope topography concentrates water into un-channelled depressions or ephemeral channels. They are less applicable to unconfined gullies where soil dispersion dominates across long headcut fronts (e.g., Figure 1) and leads to sub-surface erosion and failure of large soil blocks.

Engineered structures at semi-confined headcuts can be constructed out of a wide variety of materials and designs. Crothers et al. (1990) provided a detailed review of headcut stabilization structures used in New South Wales during the 1970s and 1980s. More detailed designs for flumes and chutes are provided in the ‘Earthmovers Training Course’ manual (Adams and Mitchell 1991). Armoured chutes carry water over an inclined slope and dissipate the water in a stilling basin at the gully floor level. They are suitable for headcuts > 1 m high and can be made out of rock, concrete, fabriform concrete, rubber matting and PVC (Figure 69a). Drop structures let water flow off a step onto other steps or a stilling basin. They are more appropriate for headcuts < 1m high and can be made out of rock, gabion, concrete, concrete sandbags, concrete blocks, sheet pile, and timber (Figure 69b; Figure 72). Most structures are designed with cut-off walls (trenches) at the inlet, both at depth into the soil and laterally, in order to prevent water tunnelling around the structure in unconsolidated soil. Alternatively, drainage pipes in the soil can be installed. Incorporation of vegetation into these structures using bioengineering is becoming more common.



a) b)

Figure 69 Generic design examples of a) chute structures and b) drop structures used to safely route overland runoff over a gully headcut (from Crothers et al. 1990).

The long-term effectiveness of chute and drop structures at headcuts greatly depends on their engineering design and the extent to which factors such as soil dispersibility, geomorphic position and processes, and design water discharge are taken into account. Many poorly designed drop structures fail within several years (Figure 70a). More elaborate drop structures can be stable and long lasting (Figure 70b), but costs per structure can restrict their use to the most strategic sites. Crothers et al. (1990) discusses some of the relative costs (1987 prices) of different types of drop structures. However, even well-constructed drop structures can fail due to factors away from the drop structure, such as soil piping in highly dispersive soils (Figure 71).

Additional research studies are needed in northern Australia on the effectiveness, stability, and geomorphic impacts of engineered structures at gully heads (chute and drop structures), especially in dispersive or sodic soils along wide gully fronts. This is relevant due to the common long-term failure of grade control structures in gullies with dispersive soils (see reviews in Sections 7.11.1 and 7.12.1).

a) b)

Figure 70 Drop structure examples in the Normanby catchment using a) geo-textile blankets installed at a gully headcut in a failed attempt to protect the soil surface and funnel overland runoff over the headcut, and b) a concrete drop structure and stilling basin at a gully headcut upstream of a road culvert.

a) b)

Figure 71 a) A prefabricated drop structure (*sensu* Yadav and Bhushan 1994) placed at an alluvial gully headcut in India, and b) water bypassing of the drop structure due to piping and tunnel erosion through the dispersive alluvial soils upslope.

Figure 72 A rock gabion drop structure at a linear gully headcut below a road drain in the Normanby catchment. Note that the structure is not well embedded into the banks of the gully headcut.

7.11 Physical Grade Control Structures Within Gully Channels

7.11.1 Literature Review

7.11.1.1 Grade Control Structures Within Gully Channels

Grade control structures are natural or engineered structures used to 1) control channel-bed incision (degradation), 2) control the grade (slope) of unstable gully, creek, and river channels, and 3) trap sediment. They have been engineered by humans for thousands of years to trap water and sediment in small headwater channels for agricultural purposes (e.g., Norton et al. 2002), and most recently in human history to completely engineer channels destabilised by human disturbance (Neilson et al. 1991; Watson et al. 1999). Grade control structures such as check dams have been the most common method utilised historically in attempts at stabilizing gullies (e.g., Heede 1974; 1976; 1978; Geyik 1986; Lal 1992; Grissinger 1996; NRCS 2007ab). However they have not necessarily been the most successful (Section 7.11.1.2 below). Gully check dams are most often utilised in semi-confined or confined gullies eroding into hillslopes, and less often in unconfined alluvial settings where gully scarp fronts can be extensive.

Grade control structures can be constructed out of a variety of materials such as rock riprap, gabions, compacted earth fill, concrete, steel sheet piling, steel mesh and posts, treated lumber, natural large woody debris (LWD), woven brush or brush debris, live vegetation such as willow fences or other species, sand bags, soilcrete bags, or other locally available material. They function by providing hard-points and artificial-steps on the bed of channels that resist erosion, reduce upstream slope and stream power, and dissipate energy. They function best where they can be tied or keyed into adjacent banks or slopes so that water does not erode around and outflank the structure. They can be designed into a variety of three-dimensional forms (check dams, weirs, drop structures, flumes) that influence both channel geometry and hydraulics (Watson et al. 1999). Their successive spacing depends on initial and desired slopes. For steep channels, structures are typically spaced so that the upstream structure does not influence the water and sediment storage capacity of the downstream structure. When spaced more closely, they can form a series of step-pool sequences; whereas with wide spacing in low gradient rivers they function more as low broad riffles. Thus grade control structures can be adapted to meet the site specific rehabilitation needs and geomorphic conditions.

In North America, for thousands of years the Zuni Native Americans have utilised brush structures arranged cumulatively along longitudinal profiles of incising gullies and arroyos to control incision and trap water and sediment for agriculture (Norton et al. 2002). The interwoven or intertangled brush structures act as semi-permeable barriers to flow and water that retain runoff, reduce velocities and erosive forces, trap sediment, and increase soil moisture. Depending on structure spacing, they can be cost effective and just as functional as more engineered structures (Gellis et al. 1995). Further south in Mexico, check dams made of layered earth and shrubs have also been traditionally used to control gully erosion and trap sediment (Bocco 1991). However, these types of vegetative structures can suffer from decay over time without maintenance (Peterson and Branson 1962; Law and Hansen 2004).

More modern engineering structures for gully grade-control have come into vogue over the last century. The use of loose rock, gabion and wire-fence check dams for gully control has been extensive in the United States, with numerous design specifications (Heede 1974; 1978; Gellis et al. 1995; Law and Hansen 2004; NRCS 2007b). In larger incised gullies and stream channels, more elaborate grade control structures have been used, such as corrugated-steel drop-pipes through earthen embankments across gullies (Shields et al. 2002; Law and Hansen 2004; Wilson et al. 2008), and larger rock, concrete, and steel drop structures and weirs (Neilson et al. 1991; Mendrop and Little 1997; Watson et al. 1999; NRCS 2007a). Interestingly due to the large environmental impacts of heavily engineered structures, the use of natural materials such as large wood and brush has increased for stream stabilization in attempts to mimic natural forms and processes (Slaney and Zaldokas 1997; Abbe et al. 2003; Shields et al. 2004).

In Australia, a variety of techniques and materials have similarly been used for installing check dams in gully systems. One common and cost effective design for sequentially-stepped grade-control in confined channels has been to use steel-wire mesh and posts anchored across gully cross-sections to trap sediment and debris behind the weirs (Crouch 1984; Armstrong and Mackenzie 2002; Jenkins and McCaffrey 2008). However, outflanking these structures in dispersive soils can be problematic once filled with sediment. Grade control weirs have additionally been constructed out of sequentially-stepped loose or interlocking rock or rock-filled gabions. Small earthen dams placed sequentially along gully drainage lines are also common as larger grade control structures, which can also be equipped with diversion banks and ditches that spread floodwater outward from the dam and away from the gully and disperse it across pastoral fields (Quilty 1973a; 1973b). Over time, designs for gully control and stabilization have become more elaborate and expensive, including larger rock and concrete chute and drop structures (Crothers et al. 1990; Bartlett 1991; Carey 2006; Jenkins and McCaffrey 2008). Most recently, engineered large woody debris structures have been utilised for grade control in small channels and large rivers (Brooks et al. 2004; 2006a; 2006b; Daley and Brooks 2013).

Gully check dams in other countries around the world have also developed similar or innovative techniques and materials. In Africa, Nyssen et al. (2004) describe soil conservation measures in the mountainous terrain of Ethiopia that have installed >70,000 loose-rock check-dams in gullies and ephemeral channels. They are constructed by hand employing local volunteer labour, utilizing local rock fashioned into compound rock steps and weirs. In finer-grained soils in Nigeria, Okagbue and Uma (1987) describe the use check-dams made out of wood wicker fences (timber, planks and pile) that are constructed in tandem, interwoven with wire and rope, and backfilled with compacted earth. In India, sand bags fashioned into compound weirs are cost effective and relatively easy to install with local labour. More elaborate drop-structures are also heavily utilised to control the grade of agricultural fields above reclaimed gully channels and networks (Yadav and Bhushan 1994; 2002; Yadav et al. 2003). In Nepal, check dams made of rock gabion and pre-cast concrete blocks were effective in trapping sediment and reducing headcut retreat into alluvium on a large terrace (Higaki et al. 2005). In mountainous terrain in Spain, large check-dams (2-15m high) have been constructed to retain sediment in confined ephemeral and gully channel segments, with dams engineered out of local rock, cobble, and cement mortar (White et al. 1997; Alcoverro et al. 1999; Boix-Fayos et al. 2007; 2008; Castillo et al. 2007).

In the Chinese Loess Plateau region, hundreds of thousands of check dams of various sizes and designs have been constructed to store sediment for grade control, sediment and water storage, local agricultural production in the impoundment area, and reduction in downstream sediment loads (Xu et al. 2004). Often these check-dams are not in gullies per se, but in large creeks and river channels in confined valleys draining from extensively gullied catchments. Many are large, low-head, earthen or concrete dams up to 100m wide with spillways and foundations designed for peak flood events. Collectively these check-dams store over a half-billion m^3 of sediment and create over 3000 km^2 of new farmland (Xu et al. 2004).

7.11.1.2 *Effectiveness of Grade Control Structures Within Gully Channels*

Despite the common usage of grade control structures around the world for gully control, sediment retention and/or yield reduction, only a handful of studies in a piecemeal fashion have critically assessed their short- or long-term effectiveness. This is especially true in Australia, where literature advocating grade-control structures is common but literature on their long-term functionality is sparse. Due to the dynamic nature of fluvial channels, monitoring and maintenance of all-sized grade control structures are key to their long-term successes and functionality. Rarely are monitoring and maintenance programs adequately funded to ensure the long-term success of these rehabilitation structures.

In southwest USA, Gellis et al. (1995) assessed the stability and functionality of 47 mostly earth and some rock check-dams (1-10m high) in large gullies (ephemeral arroyo channels). He found that 60% had been breached or outflanked and 65% were more than 50% filled with sediment. Interestingly, of 23 rock and brush structures (i.e., Norton et al. 2002), only 36% had been breached or were prone to breaching, with relative success attributed to their frequent spacing. Failure of structures occurred due to soil piping, flood scour on the structure, downstream headcutting, channel evolution, and a general lack of maintenance (Gellis et al. 1995). In an earlier appraisal of hundreds of erosion-control structures and types in arid Arizona and New Mexico, Peterson and Branson (1962) found that over half the structures had failed within a few years. Rock and brush grade-control structures in gullies had the highest failure rates compared to earthen dams and water spreaders, which were attributed to poor construction standards on top of unconsolidated material prone to piping, outflanking and erosion.

In Wyoming (USA), Marston and Dolan (1999) discussed the failure of two-dozen large check-dams built to retain sediment from Eocene claystone and sandstone badlands. The dams failed from a lack of maintenance and large intense convective storms, rereleasing millions of m^3 of sediment back into the system. Despite the short lived nature of many of the check dams that also failed to target regional areas of concentrated erosion, land management efforts still resulted in a 25% reduction in sediment load over decades, attributed to other rehabilitation measures such as destocking fragile desert rangelands.

In Tennessee (USA), Barnhardt (1989) revisited a gully stabilization project area 50 years after the construction of hundreds of log check dams to control gully erosion and the conversion of farmland to forestland. Most of the structures had failed due to high rainfall events, improper spacing and construction, lack of maintenance of structures, excess surface water inflow from roads, and most importantly from the ongoing geomorphic adjustment and evolution initiated by land-use disturbance decades before. Barnhardt (1989) concluded that "*reclamation techniques must address the underlying geomorphologic processes involved with the development and modification of stream channels and hillslopes*".

In Colorado (USA) rangelands, Weinhold (2007) reviewed the 40-year success story of numerous gully control measures (check dams, cattle exclusion, revegetation) originally implemented by Heede (1974; 1976; 1978) in hillslope rangelands. The stabilization success of most gully grade control structures was attributed to 1) vegetation management via cattle exclusion that increased vegetation resistance and reduced water yield driving erosion, 2) the careful hydraulic design of grade control structures including design flows, dimensions, and keying structures into gully sidewalls and beds to reduce outflanking and scour, and 3) the overdesign and abundance of structures that prevented cumulative failure and sediment yield. These studies highlight the careful thought, implementation costs, and process-based approaches needed for holistic gully erosion control at the catchment scale.

In Ethiopia, Nyssen et al. (2004) documented the frequent collapse of loose rock check-dams (39% of 400 dams after 2 years) and the need for frequent maintenance. Their failure was related to channel slope and catchment area used as a proxy for stream power. Bypassing of dams due to soil piping and outflanking in cracking Vertisols was also noted. Dam spacing frequency, height, and design with a spillway and apron were also important factors for stability. In Nigeria, Okagbue and Uma (1987) documented the failure of many timber-fence check-dams due to undercutting and soil piping through or around the dams. In India, Yadav and Bhushan (1994) also noted the problem of soil piping undermining in-situ constructed drop structures used for gully grade-control. Florido (1985; cited in Lal 1992) in the Philippines found that rock check dams were more effective at sediment retention than log, brush or hogwire check dams. For large rock and mortar check-dams in Spain, Boix-Fayos et al. (2007) reported that 72% of 58 structures were completely filled with sediment and 81% showed signs of erosion and bed coarsening downstream of the dam due to turbulent scour and sediment starvation. Similar results in a nearby catchment by Castillo et al. (2007) showed that 81% of 36 structures had filled in with sediment and 2 structures had failed. Most dams also experienced erosion downstream, but the net effect of storage upstream to erosion downstream was overall storage of sediment.

In New Zealand, chronic high sediment supply from large fluvio-mass movement gully complexes, initiated following native forest clearance, has largely overwhelmed and buried early attempts at gully stabilization using large-scale check dams, vegetation fascines, and even levees to protect agricultural fields (Marden et al. 2005). However, similar grade control structures in smaller catchments < 1 ha have been more successful (Marden et al. 2005). Overall, large-scale reforestation was much more effective at reducing sediment yields at the catchment scale (DeRose 1998; Gomez et al. 2003; Herzig et al. 2011).

The complete failure of check-dams and grade control structures, similar to larger dams, can have catastrophic impacts on downstream channel habitat, accelerated sediment supply, and human safety and infrastructure. For example, a flash flood in the Spanish Pyrenees resulted in the failure of ~ 40 rock and mortar check-dams (2-15m high) that released

50,000 m^3 of stored sediment that contributed to the death of 87 people (White et al. 1997; Alcoverro et al. 1999). In China, the failure of more than 80% of the check-dams in the Shanbei region in 1977/1978 during major rainfall-runoff events highlighted the need for proper design of check-dams (Xu et al. 2004). As a result fewer check-dams are being built due to additional costs to engineer stability for design-floods. Li et al. (2003) also noted the periodic failure of check dams (used for farming) during mountain flood torrents.

While many studies document the trapping and storage of sediment behind check-dams as a mitigation measure of upslope sediment supply, fewer document the success of actually stopping gully incision or the head-ward growth of gully head-cuts. Several authors emphasise the importance of the exact timing and location of structural intervention relative to the stage of gully channel evolution (*sensu* Simon and Hupp 1992)(Okagbue and Uma 1987; Gellis et al. 1995; Simon and Darby 2002). For example, Simon and Darby (2002) document the relative ineffectiveness of large grade-control structures at reducing channel erosion rates in Mississippi (USA) because intervention occurred too late in the evolutionary cycle. They recommend that to be effective, grade-control structures would need to be placed just upstream of active headcuts during the early stages (I or II) of channel evolution when active incision and erosion is at its greatest. For this purpose, hundreds of corrugated-steel drop-pipes through earthen embankments (a.k.a., drop pipe structures) have been built at or above gully heads in the region (Shields et al. 2002; Wilson et al. 2008). However the effectiveness of these structures at reducing long-term sediment yields is unknown, especially due to their relatively short life-spans and common failure (Wilson et al. 2008). Their relative contribution to sediment reduction is also unknown, due to multiple catchment-scale soil-conservation measures (tree planting, riparian buffer strips, grass strips, agricultural land retirement, and grade control) and inherent channel recovery through geomorphic evolution (Kuhnle et al. 2008). Increasingly it is becoming apparent that structural intervention is not the panacea for gully and channel stabilization, with a renewed emphasis on working with mechanistic processes of natural channel evolution that primarily responds to driving and resisting forces and the inputs of energy and material (Barnhardt 1989; Callahan 2001; Simon et al. 2007).

7.11.2 Case Study 5: Grade Control Structures on Red Ferrosol (Basalt) Soils

As part of a cooperative cost-share project through the Reef Rescue program, a Normanby catchment landowner installed a series of rock grade control structures (check dams) along shallow gullies in red ferrosols using locally sourced basalt boulders and cobbles. Gully areas were also seeded with perennial grass (Floren bluegrass, *Dicanthium aristatum*) to compete with annual invaders (Grader grass, *Themeda quadrivalvis*), as well as spelling cattle in the area to promote seed recruitment and improved grass cover. The rock structures were placed using a tip-truck to back-fill the gullies, as well as a front-end-loader to move material into place. At most sites, machinery was not used to key (dig) the structures into the bed and banks of the gully, nor to specifically place individual boulders to lock the structures into place.

Before and after photo monitoring (with no quantitative data) suggested the rock grade control structures had mixed results in terms of gully stabilization and sediment retention. In narrow gullies where back-filled rock had good contact with the bed and banks, the structures were stable and retained sediment during runoff events (Figure 73a). Improved grass cover on the gully walls from seeding and spelling also promoted soil stabilization (Figure 73b). However, cattle were attracted to newly established Floren bluegrass within gullies (Figure 73c), which continued to promote ‘soil pugging’ by cattle hooves (Figure 73d) despite improved cover. Continued wet season spelling will be needed to promote additional cover through grass seeding and spreading within these gullies.

Within larger gullies, bigger volumes of back-filled cobbles, boulders and mixed soil were used for gully grade control. This worked well along fence-line roads where check dams were used as armoured crossings of gullies with rock and soil matrix well embedded into the bed and banks (Figure 73e). In contrast, boulder and cobble check dams that were loosely placed on the bed of larger gullies were easily outflanked by running water (Figure 73f). These structures were not embedded or keyed into the banks and bed of the gully using a backhoe or excavator. They also did not contain a finer matrix of rock and soil to prevent water piping through or around the structure. These ferrosols are prone to drying and cracking through the dry season, especially if grass cover is lost on exposed gully banks. This cracking can promote locations of water piping around grade control structures. Therefore, it is essential that any grade control structures are keyed (embedded) into the banks and beds of gullies using a backhoe or excavator. Any excavated soil can be used to backfill the upstream side of the abutments and can be used as matrix material within coarser cobbles and boulders. However, extreme caution is needed during any excavation into gully banks and beds so that local erosion is not accelerated from collateral damage from machine use. After grade control installation, the gully area should be liberally seeded with appropriate grass species at the beginning of the wet season and if possible spelled from grazing to allow good grass establishment and ground cover.


a) b)
c) d)

e) f)

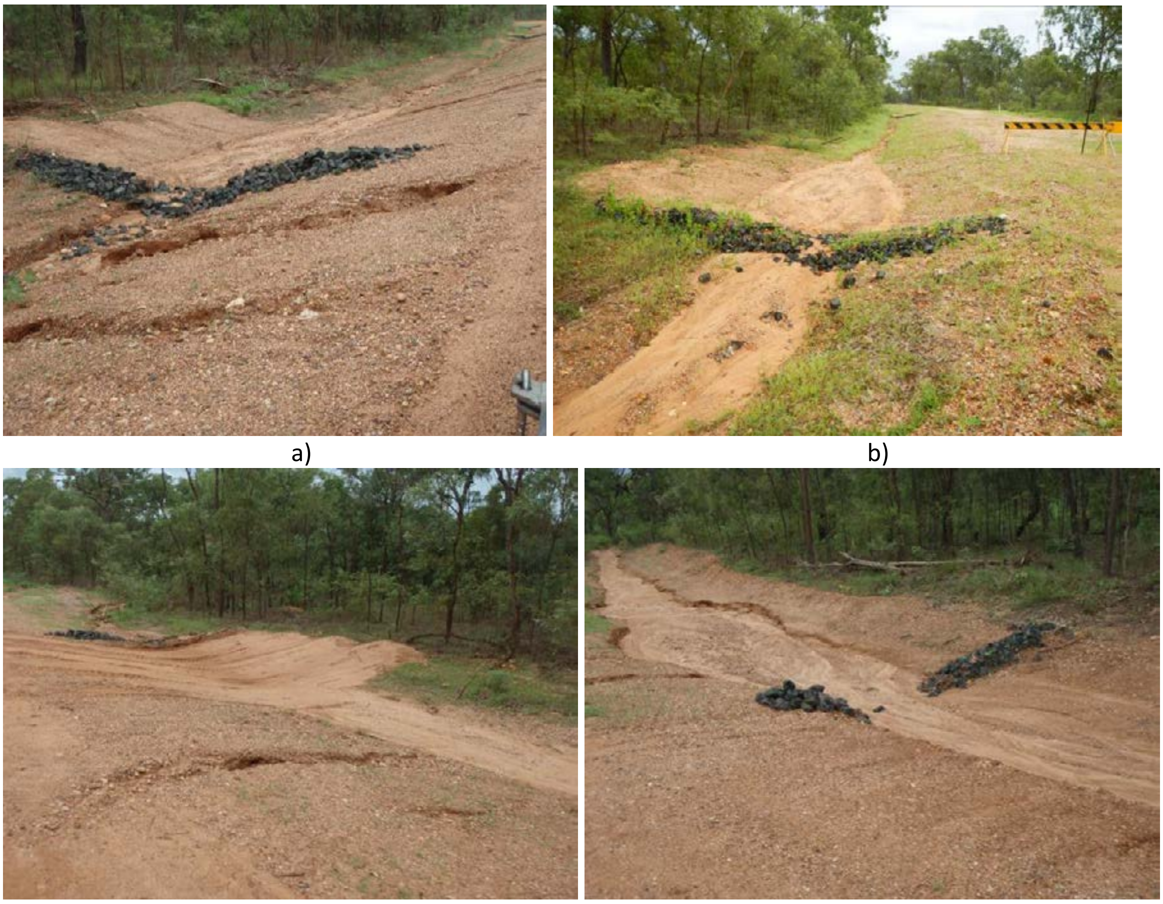
Figure 73 Gully grade control structures in red Ferrosols in the Normanby catchment showing a) small effective boulder check dam in a narrow gully during the dry season, b) loose boulder check dam after the wet season, c) cattle preferentially consuming Floren bluegrass (*Dicanthium aristatum*) planted to stabilise a gully, d) improved grass cover but remaining exposed soils after the wet season due to 'soil pugging' by cattle hooves, e) an earthen/rock dam (gully plug) across a gully along a fence-line road, and f) an outflanked loose boulder check dam in a larger gully during the dry season (boulders were not keyed into the bed and banks of the gully).

7.11.3 Case Study 6: Grade Control Structures along Normanby Main Roads

Along the Peninsula Development Road through the Normanby catchment, road construction crews have been using rock grade control structures in roadside ditches to prevent gully erosion in the ditch and trap coarse sediment from the road (Figure 74). Less effective and often poorly placed and designed silt fences are also commonly installed along man roads (Figure 75). At times these structures are placed following BMP guidelines (e.g., Witheridge 2009; 2012), while more often they are placed in an ad hoc fashion with mixed results. Rock grade control structures are typically placed every 50+ m depending on road slope, while V-drain spacing to relieve ditch water was measured to be 144 m on average (Gleeson 2012). Rock structures are constructed in a V or trapezoidal cross-section shape and at times are keyed (embedded) into the ditch bed and banks to prevent outflanking or undermining. Rock size varies but is typically minus 300 mm.

Qualitative observations through several wet seasons indicated that these rock grade control structures had mixed results in terms of road ditch stabilization and sediment retention. Due to the nature of the road base, high traffic and intense rainfall, large amounts of water and fine and coarse sediment are transported off these road surfaces (1029 mg/L mean suspended sediment concentration; 15 to 25mm/yr of surface gravel erosion; Gleeson 2012). Sheet and rill erosion are common place (Figure 74a), as is the potential for gully erosion at most sites (Figure 74b; Gleeson 2012). Many grade control structures are effective at trapping coarse sediment eroding from the road (Figure 74a), but often become buried by upstream sediment deposition (Figure 74b), and frequently require re-excavation to retain their sediment trapping function (Figure 74c). When not maintained or overwhelmed with water and sediment, these structures often fail through breaching or burial (Figure 74d). They also can become completely outflanked by sediment deposition or lack of keying rock into the ditch banks.

These examples highlight the importance of 1) the frequency of road ditch water diversion structures to minimise water stream power and sediment delivery to any one location (Table 7; Johansen et al. 1997; Jolley 2009; NSWOEH 2012), 2) the frequency of grade control structures to match sediment trapping capacity to catchment area, and 3) the height, volume, rock size and abutment design of structures to minimise breaching, outflanking or complete burial, 4) the potential for headcut incision up steep V-drains to undermine structures, 5) the need for regular long-term maintenance, and 6) the limited capacity of grade control structures to mitigate the impact of upstream erosion not addressed through more direct actions (more resistant road base, better water drainage, improved road location and design).



a) b)

c) d)

Figure 74 Grade control structures along the Peninsula Development Road: a) sheet and rill erosion off the road and trapping behind a rock structure, b) sediment wedge upstream of a structure, c) maintenance excavation of trapped sediment accumulation, and d) breaching of a structure due to excess water runoff and channel incision along a steep V-drain.

Figure 75 A inadequate silt fence for erosion control that did not follow BMP guidelines (Witheridge 2009; 2012), was not embedded into gully banks, and is being overwhelmed by road sediment due to overzealous clearing and improperly designed road drainage.

Larger examples of grade control structures exist along the main roads through the upper Normanby catchment. Where gully headcuts have migrated through sodic soils toward main roads, large boulder grade control structures have been installed by road crews (Figure 76a). To ensure stability of the structures and old headcut, angular rock was imported and spread across the upstream channel and headcut to protect underlying sodic soils to scour and incision. In another large gully location, a full grade control weir was constructed out of gabion (wire mesh filled with rock) that was keyed into the underlying bed and gully banks (Figure 76b). This has effectively stabilised the channel grade upstream of the structure through the bridge, but channel scour continues to threaten the downstream side of the structure due to turbulence, necessitating the import of additional coarse rock.

Figure 76 Examples of large grade control structures on Normanby main roads: a) an alluvial headcut that has been partially stabilised by a large rock grade control structure and rock apron downstream of new road culverts, and b) gabion basket (rock filled) grade control structure below a highway bridge.

7.11.4 Case Study 7: Grade Control Structures in Sodic Duplex Soils on Crocodile Station

Rock and wood grade control structures were installed at numerous gully headcuts at Crocodile Station (Table 6) to better quantify their functionality at reducing erosion and trapping sediment. Weir structures were keyed (dug) into the bed and banks of the gully to prevent undermining or outflanking, which has occurred at other grade control structures installed in the Normanby catchment (Sections 7.11.2 and 7.11.3). Observations at CRGC1 after two wet seasons (WY 2012 & WY 2013) indicated that both rock and wood grade control structures were stable and retained water and sediment (Figure 77). However, these gully headcuts were not extremely active, partially due to below average rainfall. Future assessments will be needed at these sites, along with trials of grade control structures at rapidly advancing gullies and headcuts (Section 7.11.5; Figure 81).

Some preliminary lessons learned include that collateral damage from excavator machine footprints during installation can be significant and locally increase erosion at least temporarily (Figure 79a). Exotic grass species were sown in disturbed areas and gully banks, in additional to straw mulch. Similar to experimental plots with just grass and straw mulch (Section 7.13.5; Figure 107; Figure 108; Figure 109) germination and growth success of grass was very limited at grade control sites (Figure 55; Figure 56; Figure 79b). Combinations of reshaping gullies, surface grade control and hydromulching application will be reviewed below (Section 7.13). Soil amendments help improve vegetation establishment.

Table 6 Grade Control Treatment Sites at Crocodile Station

Gully Headcut Site #	Treatment	Terrestrial Laser Scanning (TLS)	Latitude / Longitude	Number of Structures	Estimated Total Cost ($)	Photo Examples
CRGC1-32	Control, No Treatment	Yes	-15.709462 / 144.676439	0	0	not shown
CRGC1-33	LWD Grade Control	Yes	-15.709405 / 144.676869	5	$ 1000	Figure 77 Figure 78b
CRGC1-34	Rock Grade Control (25t)	Yes	-15.709131 / 144.676814	5	$ 1800	not shown
CRGC1-40	Regrade slopes, gypsum, hydromulch, LWD grade control	Yes	-15.708456 / 144.676943	6	$ 6000	Figure 97 Figure 98
CRGC57	Control, No Treatment	Yes	-15.704618 / 144.687048	0	0	not shown
CRGC58	Rock Grade Control (20t)	Yes	-15.7043 / 144.687096	5	$ 1500	Figure 78a
CRGC59	LWD Grade Control	Yes	-15.703956 / 144.687154	5	$ 1000	not shown
CRGC61	Control, No Treatment	No	-15.709441/ 144.679948	0	0	not shown
CRGC60	LWD Grade Control	No	-15.709216 / 144.679601	8	$ 1000	Figure 80

a) b)

Figure 77 Examples of grade control structures used at a) CRGC1-34 utilizing sequential rock weir keyed into the bed and bank, and b) CRGC1-33 utilizing sequential small-wood weirs keyed into the bed and banks.

a) b)

Figure 78 Examples of water and sediment trapping behind a) rock (CRGC58)and b) wood (CRGC1-33) grade control structures.

a) b)

Figure 79 Examples of a) soils disturbed by an excavator during grade control structure installation at CRGC58, and b) poor revegetation success following grass seeding.

a) b)

Figure 80 Wood grade control structures placed above and below a gully headcut (CRGC6061) in a) Dec-2011 after installation and b) in April-2012 after the first wet season inside a cattle exclusion fence (Figure 45).

7.11.5 Case Study 8: Proposal to Install Large Drop Structures at Crocodile Gap Gullies in Conjunction with Cattle Fencing for Vegetation Rehabilitation

Along the Laura River frontage at Crocodile Gap and Yards (-15.668992°S; 144.592765°E; Figure 38; Figure 83), numerous tributary catchments are undergoing major rapid change in the early phase of gully evolution (Brooks et al. 2009; Shellberg 2011). Major alluvial gully headcuts are rapidly eroding up the channel-less hollows of each catchment (Figure 81a), with erosion rates up to 20 m/yr but more typically 5 m/yr (Figure 83). Sediment yields have been estimated at up to 1,500 tonnes/year per headcut. Once these linear headcuts reach their maximum extent longitudinally, they will begin to widen out into a more ‘amphitheatre’ shaped gully similar to more mature gullies (e.g., Figure 1; Brooks et al. 2009). By this stage, many tens of thousands of tonnes of sediment will have been eroded.

Runoff in each catchment has been accelerated by overgrazing, the invasion of grader grass (*Themeda quadrivalvis*) and other weeds, and dense cattle tracks (pads) that concentrate and funnel water into hollows and gully headcuts (Figure 82). While vegetation management and cattle exclusion could help protect the soils from heavy rain, reduce water runoff, and provide erosion resistance and roughness, cattle exclusion alone will not stop these headcuts. A combined effort of cattle exclusion and grade control (or drop) structures at gully headcuts will be needed to reduce erosion in these catchments.

Currently these gullies are at a critical stage of intervention, and if stopped now early in the cycle of gully evolution, large amounts of sediment could be prevented from eroding into the Laura River. It is proposed to trial large gully headcut stabilization techniques (drop structures and grade control structures; Sections 7.10 and 7.11) at a few of these headcuts (CGGC4-8), while keeping many as an erosion 'control' (CGGC1-3). These types of structural interventions could be appropriate and cost-effective per unit sediment yield reduction at this location. Examples of possibly appropriate structures have been installed at nearby gully headcuts eroding into the Peninsula Development Road at Crocodile Gap (Figure 81b).


a) b)

Figure 81 Examples of a) large alluvial gully headcut eroding into a floodplain hollow (CGGC6; Figure 83), and b) an alluvial headcut that has been partially stabilised by a large rock grade control structure downstream of culverts on the Peninsula Development Road near Crocodile Gap.


a) b)

Figure 82 Examples of a) sheet flow and erosion along a floodplain hollow above a gully headcut (CGGC6; Figure 83; Figure 81a), and b) cattle tracks (pads) funnelling sheet flow down into the same floodplain hollow. Note the low vegetation cover and roughness needed to slow water flow and protect the soil surface from erosion.

In conjunction with the proposed trial engineering intervention at these headcuts, it also proposed to install a 30 ha (2.3 km) cattle exclusion fence around several treatment gullies

(Figure 83; CGGC4-8) in order to improve vegetation conditions and reduce water runoff. Neighbouring catchments could be used as a control with continued grazing (CGGC1-3). Different fire management regimes and weed control could also be trialled to increase perennial grass cover, in cooperation with the station manager and local Traditional Owners. In November 2012, thirty-two (32) baseline ('before') vegetation plots were installed and surveyed (Figure 83), according to the same vegetation monitoring procedures (Appendix 10.1 and 10.2). Sixteen (16) plots were surveyed inside the future exclosure and 16 outside, with 4 plots for each of the four major geomorphic units per treatment. Plots were stratified by geomorphic unit (head scarp, uneroded hillslope, hollow, gully bed/banks). Erosion 'before' conditions were surveyed by repeat airborne LiDAR in 2009 and 2011.

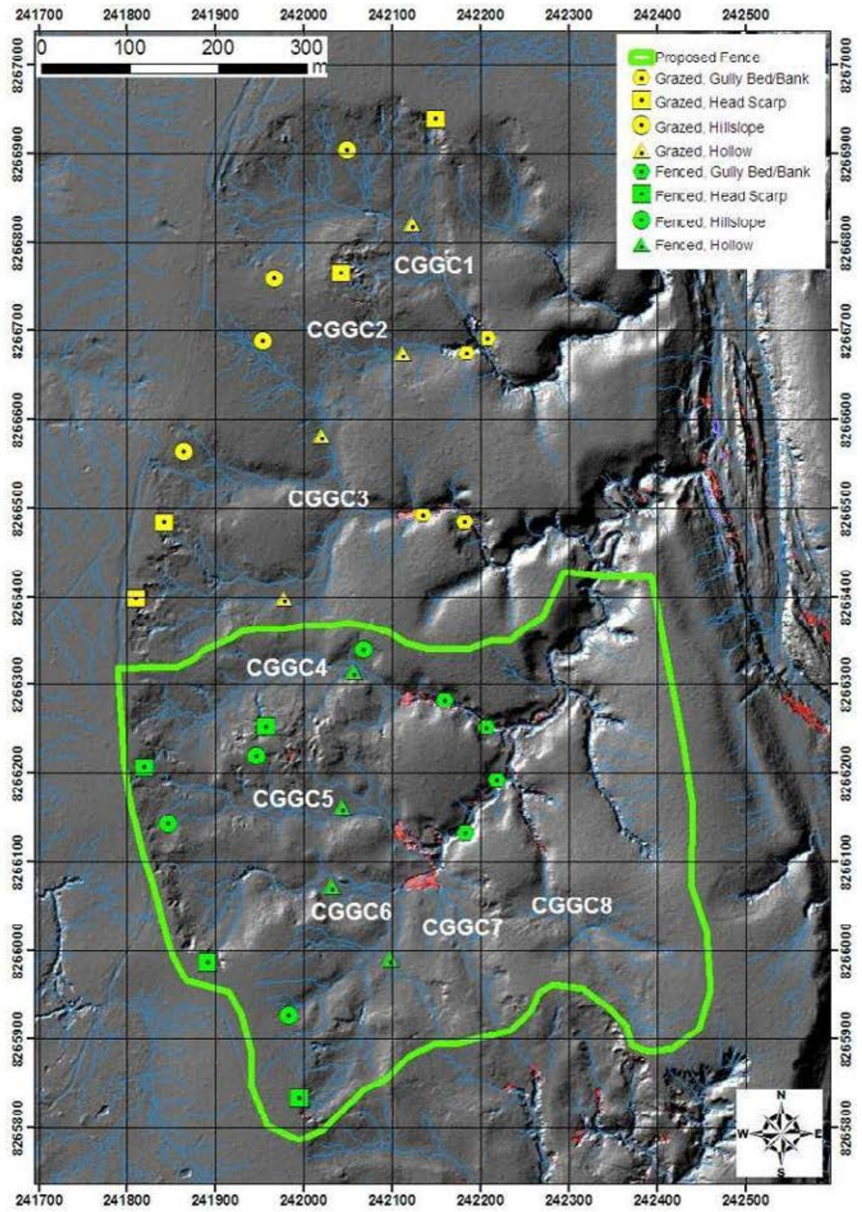


Figure 83 Catchment hollows, gully headcuts (red), baseline vegetation plot locations, and a *proposed* exclusion fence (green) at several gully catchments (CGGC1-8)that are tributary to the Laura River near Crocodile Gap and Yards (15.668992°S; 144.592765°E). Note that red areas are zones of active gully erosion between 2009 and 2011 repeat LiDAR.

Preliminary results from November 2012 surveys indicated that % total cover levels were low for head scarps and moderate for hillslopes, hollows, and gully bed/banks (Figure 84). Total cover was dominated by the mulch of dead annual grass (mostly *Themeda quadrivalvis*). The % cover of perennial grass was low in contrast at all sites (Figure 84). These low perennial grass cover conditions can promote the acceleration of water runoff during rainfall events (Figure 82) that can fuel the retreat of headcuts into these floodplain hollows (Figure 81).

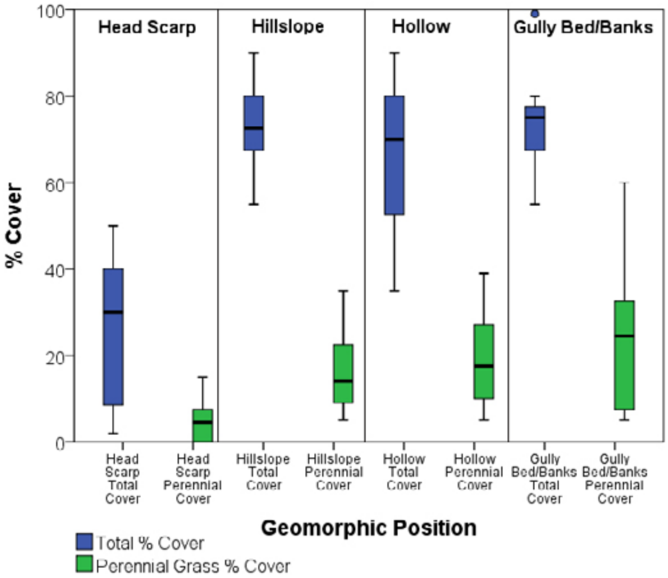


Figure 84 Differences in total and perennial grass cover during November 2012 baseline surveys at the proposed Crocodile Gap cattle exclusion site, clustered by different geomorphic units.

If this proposed physical and biological management trial is fully implemented with future funding, long-term data over the next decade on vegetation conditions, water runoff and gully erosion will be needed to tease apart the influence of management treatments (e.g., fencing, grade control) versus natural variability due to rainfall or other variables. Vegetation plots would need to be surveyed annually and repeat LiDAR collected every few years to detect changes over time.

7.12 Physical Water Diversion and Retention Structures

7.12.1 Literature Review

7.12.1.1 Water Retention and Diversion Structures on Hillslopes Above Gully Heads

For controlling both water and sediment runoff and the initiation of gully erosion, numerous structural methods have been developed to retain water and sediment in-situ on hillslopes (retention structures) and/or divert water to areas where it can infiltrate without erosion (diversion structures). The goal of retention structures is to capture water and sediment locally as they move down slope, reduce slope-lengths, reduce overland flow velocities and depths, promote infiltration, increase evaporation, and increase vegetative establishment and water use. Most often structures are installed on contour in a continuous or staggered fashion perpendicular to the fall line. Large retention structures such as ponds and dams constructed above gullies and along drainage lines will be discussed further below. The goal of diversion structures is to both capture water and sediment down slope in addition to diversion of water to appropriate discharge locations, such as away from gully heads and drainage lines.

At the local scale, small check dam structures are used for soil/water retention, velocity reduction, and erosion control, especially for construction projects, road slopes and drainage ditches. These include silt-fences made of mesh fabric, straw bales, coir bundles and wattles, compost berms, and compost filter socks (Gray and Sotir 1996; NRCS 2007c; Faucette et al. 2009b). For more intensive biogeotechnical engineering of hillslopes, larger water/sediment retaining structures are used in association with vegetation planting, using structures such as concrete walls, rock gabions, rock riprap, timber and concrete cribs, and other innovative structures (Gray and Sotir 1996; NRCS 1992; NRCS 2007c). Bioengineering treatments that incorporate both physical structure and vegetation include live staking, live fascines, live crib walls, terraced brush-layers and hedge rows and berms on contour (Gray and Sotir 1996; NRCS 1992).

Once the scale of structural erosion control reaches entire or multiple hillslopes, the options change for practical or cost-effective structural control. Retention structures such as straw bales and silt fences can still be used, but labour costs increase. In forested settings, contour-felled log erosion-barriers can be used to reduce overland flow velocities and trap sediment (Robichaud et al. 2010). As with all retention structures, they can rapidly fill up with sediment and become ineffective at water and erosion control over time. This highlights the need for consistent maintenance programs or a combination of treatments to reduce water and sediment runoff from hillslopes.

In large-scale agricultural and rangeland settings where trees have been cleared or are naturally absent, water and sediment retention structures on hillslopes or plains have been constructed in sequence on contour (e.g., Figure 85) and made out of local soil material and formed into contour banks, furrows, ditches, berms, and terraces (Gifford 1978; Hudson 1987; Jackson et al. 1991; QDERM 2004b; Thomas et al. 2007). Contour structures can also be planted with grass, crops, or hedgerows to increase sediment retention (Hudson 1987; Gray and Sotir 1996).

In Australian rangelands, contour banks (e.g., Figure 85) were historically advocated by Soil Conservation Departments and used to control shallow hillslope runoff, promote infiltration, spread water, and retain soil in-situ in association with or without the use of grass, shrub or crop cover (Quilty 1972b; Bartlett 1991; Jackson et al. 1991; Tongway and Ludwig 2002; Payne et al. 2004; QDERM 2004b; Jolley 2009). Banks of various types can be constructed using either road graders or disk ploughers or bulldozers, with graders being the most economical. Continuous contour banks can be periodically spaced downhill as a function of slope to retain and diffuse concentrated water flow. Alternatively, contour banks can be constructed with periodic gaps and adsorption banks downslope of gaps (i.e., gap absorption and gap spreader banks), which provide the dual functions of energy dissipation and water spreading to maximise use (Quilty 1972b). The spacing and storage volume of contour banks are a function of slope and expected rainfall-runoff volumes of a given magnitude-frequency. Maintenance of contour banks is commonly needed over time (~decade) to repair breaches in the banks from water or stock or traffic and maintain the water and sediment trapping capacity.

Figure 85 An example of contour banks (berms) installed in a cleared pasture (slope from left to right) in the Lakeland area of the Normanby catchment to control shallow hillslope runoff, promote infiltration, spread water, retain soil in-situ, and reduce water and sediment runoff to adjacent creeks. Note that this treatment is only applicable to already cleared paddocks.

In extremely degraded pastures where scalds are common or vegetation cover has been removed, more intensive water retention and vegetation rehabilitation measures can be instated, especially on relatively flat land in non-hilly country. Small, frequent, and cumulative water-ponding banks can be used to reclaim scalded duplex soils in semi-arid rangelands by retaining and infiltrating water and leaching salts (Jones 1969; Cunningham 1974; Thompson R., 2008; Jolley 2009). On highly degraded pasture land where vegetation has been lost, a variety of mechanical methods are available to disk, furrow or pit the soil on contour and simultaneously seed suitable vegetation species (Pressland et al. 1988; Tongway and Ludwig 2002; Payne et al. 2004; Jolley 2009). In extremely degraded situations these intensive measures can be quite successful, especially if stock numbers are carefully controlled or eliminated (Tongway and Ludwig 2002; Payne et al. 2004).

For gully stabilization or the reduction in gully initiation, water diversion banks or ditches are often used immediately upslope of a gully headcut or along gully channels to intercept water before it converges into an existing or potential gully area (Quilty 1972a; 1972c; NRCS 2007b). In Australia, these earthen banks are typically constructed at a subtle but appropriate grade to divert water but prevent scour in the ditch (Quilty 1972c; Bartlett 1991; Jenkins and McCaffrey 2008). However, extreme caution is warranted in selecting exactly where diverted water is released for dissipation, as discharge areas can become zones of concentrated water flow and can initiate or accelerate gully erosion in unintended locations (Haigh 1984; Quilty 1986). Engineered waterways (grass or rock) can be constructed to receive diverted water and dissipate energy (Stannard 1977; Bartlett 1991; Pinkerton and Greentree 1991; Poesen et al. 2003; NRCS 2007b; Jenkins and McCaffrey 2008; QDERM 2004c). Unfortunately, the statement by Gifford (1978) that "*many of these efforts [to structurally control runoff] suffer from lack of data regarding actual influences of treatments on resources*" still remains partially true today, especially for tropical Australia.

"*Diversions constructed above the gully area direct run-off away from gully heads, and discharge it either into natural waterways or vegetated watercourses, or onto rock outcrops and stable areas which are not susceptible to erosion. Surface water must not be diverted over unprotected areas or it will cause new gullies*" (Geyik 1986).

In Spain, small earthen banks (~30cm high) are often built by farmers to divert water away from gully head scarps eroding into alluvial terraces (bank or alluvial gullies) (Oostwoud Wijdenes et al. 2000). Research demonstrates that these banks can significantly reduce head scarp retreat, but Oostwoud Wijdenes et al. (2000) concludes that improper discharge of diverted water can promote gully side wall erosion, or perhaps lead to piping in dispersive soils by increasing the hydraulic head of water ponded behind banks. In India, where reclamation of gullied landscapes is essential for agricultural protection, contour banks and terraces have been effective at local water retention, spreading water for plant use between structural banks, and controlling water runoff that fuels down slope gully erosion (Haigh 1984; 1998; Yadav and Bhusman 1989; Singh 1992; Yadav et al. 2003).

7.12.1.2 *Farm Dams and Reservoirs At or Above Gully Heads*

In south-eastern Australia, small earthen dams and reservoirs are commonly built above gully heads within shallow hillslope depressions or within existing ephemeral channels (Quilty 1973a; Young 1973; Starr 1977; Greentree and Jackson 1991a; 1991b). They have the goals of trapping hillslope sediment, impounding water runoff and reducing downstream peak discharge rates, diverting water away from downstream gully heads and channels, and/or using the water locally for stock and farm uses. They are commonly advocated and partially funded by government departments and natural resource management (NRM) groups for both erosion control and farm development (Bartlett 1991; Greentree and Jackson 1991a; 1991b; Franklin et al. 2004; Carey 2006; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008). Typically these earthen dams are constructed out of compacted local clay material, dressed with stockpiles of topsoil, and provided with earthen spillways lined with clay and grass, or armoured with rock or concrete to dissipate energy

(Quilty 1973a; Young 1973; Starr 1977; Greentree and Jackson 1991a; 1991b). They are also typically associated with armouring downstream gully head scarps (see Section 7.11) to reduce headcutting into the dam foundation, or used during the complete reshaping of downstream gully channels (see Section 7.13). Retention volumes and sediment trap efficiencies depend on design, particle size fraction (sand vs. silt/clay), and dam location (tributary vs. mainstem). In SE Australia, Armstrong and Mackenzie (2002) estimated that farms dams used for gully control trapped >70% of the sediment yield and significantly reduced downstream sediment supplies, similar to other studies (Verstraeten and Prosser 2008).

In the United States, earthen dams or “drop pipe structures” are commonly built at the head of gullies (>3m deep) eroding up into agricultural fields. These structures consist of corrugated-steel drop-pipes through earthen embankments 4 to 6 m high (Shields et al. 2002; Wilson et al. 2008). They are essentially a farm dam placed immediately at a headcut. The effectiveness of these structures at reducing long-term sediment yields is unknown, especially due to their relatively short life-spans and common failure (Wilson et al. 2008). However, they can be modified for ecological benefits (Shields et al. 2002; 2007). In the United States, there are >2,000,000 small dams (<2m high) many over 50 years old (Graf 1999). Removal of these and larger dams has accelerated over the last two decades due to safety concerns over ageing infrastructure, loss of dam or reservoir functionality due to sedimentation, high costs of maintenance, and/or increasing concerns about the environmental impact of dams or dam failures (Pohl 2002).

Small farm dams are ubiquitous across Australia, and many are installed above gullies for control (e.g., Figure 21; Figure 86). The design standards and life expectancy of small dams in Australia are typically less than for large reservoirs (Pisaniello 2010), especially those constructed out of local material and targeting gully stabilization and sediment retention (Quilty 1973a; Young 1973; Starr 1977). The number, age and condition of small farm dams in Australia are unquantified. Dam failure is a major concern worldwide (Graham 1999) including small farm dams in Australia (Pisaniello 2010). When small dams are constructed on top and out of local material such as dispersive or sodic soils, tunnelling and pipe erosion can lead to their failure (e.g., Figure 21; Floyd 1974; Starr 1977; Boucher 1990). However, failure of dams and earthworks in unstable soils can be minimised if soils and earthworks are sealed and capped properly (Wickham 1976; Elliot 1979; 1980). Failure is most common during extreme flood events following long drought periods and minimal maintenance, typical for the Australian continent. For example, several earthen dams located at study sites of Armstrong and Mackenzie (2002) have deep rilling and tunnel erosion on their dam face that could threaten the future integrity of the dams (Shellberg, personal observations).

Figure 86 Example of a) a small farm dam installed above a gully head to retain and dissipate overland runoff before reaching the gully head, and b) the gully headcut below the dam still eroding from excess storm runoff out of the dam and insufficient armouring of the headcut.

Installing dams to trap sediment generally addresses the symptoms of the erosion problem rather than the causes, although grade control and water storage can be important mitigating interventions. The questionable long-term functionality and stability of using farm dams to mitigate water/sediment runoff and gully erosion needs to be balanced against more sustainable methods to control water runoff and gully erosion, such as complete hillslope and channel revegetation and/or altered land-use practices. This is especially true for dispersive or sodic soils along river frontages in northern Australia, where dam stability is a major concern. Furthermore, farm dams would not be suitable for water runoff control from wide terrace flats of river frontage that drain toward long gully scarps (breakaways) of alluvial gullies (Figure 1; Figure 2). However, in some topographic situations such as floodplain hollows and dendritic drainage ways on floodplains, dams may be suitable for runoff control above gully heads if they can be constructed to minimise failure from piping through sodic soils.

7.12.1.3 *Effectiveness of Sediment Retention Behind Dams and Grade Control Structures at the Catchment Scale*

It could be argued that damming gully systems with small or large grade-control structures and/or sediment retention dams could have the greatest effect on short-term sediment yields for large-scale sediment retention compared to other rehabilitation efforts conducted in concert (Xu et al. 2007). However over the long-term as reservoirs fill up with sediment (Gellis et al. 1995; James 2005; Castillo et al. 2007; Boix-Fayos et al. 2007), eventually fail (White et al. 1997; Graham 1999; Alcoverro et al. 1999; Pisaniello 2010), or need to be removed (Graf 1999; Pohl 2002; James 2005), these engineering measures are less sustainable compared to other methods like improved pasture vegetation management, afforestation, or land-use modification in upslope catchments. *Building sediment retention dams is a classic example of treating the symptoms rather than addressing the causes of erosion.* Nonetheless sediment retention reservoirs have been and continue to be built around the world in a variety of environments to mitigate upstream land-use impact, reduce downstream sediment supply, and provide additional water resource functions (Armstrong and Mackenzie 2002; Huang et al. 2003; Xu et al. 2004; James 2005; Rustomji et al. 2008; Zhang et al. 2008).

In catchments with severe gully erosion, water and sediment retention dams can dominate the reduction of sediment yield over time (Armstrong and Mackenzie 2002; Xu et al. 2004; Rustomji et al. 2008) and mask the assessment of the effectiveness of other soil stabilization efforts such as catchment revegetation or improved best management practices during land use. In an attempt to quantify the relative influence of gully erosion rehabilitation measures such as check-dams and land-use change toward reforestation, Boix-Fayos et al. (2008) used an erosion model calibrated to field data collected in Spanish headwater catchment (Boix-Fayos et al. 2007). They estimated that land use alone reduced sediment yield by 54% over 40 years, while large check-dams alone reduced yield by 77%. While both measures were effective, the check-dams had a short-term effect with no long-term benefits and several side effects such as scour downstream of dams and failure potential. In contrast, land-use changes resulted in permanent reductions in erosion at the sources.

In an Australian study using a similar erosion model, Verstraeten and Prosser (2008) modelled the cumulative sediment yield effect of thousands of farm dams, typically located above incised gully networks but below hillslopes. They estimated that the farm dams in sum reduced hillslope sediment yields by 120% of pre-European yields, but that post-European gully and bank erosion downstream kept sediment loads elevated at 250% above background. However a much larger mainstem reservoir downstream has almost fully mitigated sediment yields further downstream back to pre-European disturbance values. Due to overall low sediment yields to the reservoir, long-term concerns over reservoir infilling were minimal regardless of upstream land use.

7.12.2 Normanby/Mitchell Catchment Examples of Earthen Banks above Headcuts

Several examples of water retention and diversion banks above alluvial gully heads have been constructed on terraces in the Normanby and Mitchell catchments. These have most often been constructed on the edges of cleared paddocks above adjacent gully heads or more commonly along road verges to divert overland runoff from entering gullies or road ditches. Constructing earthen banks above gullies is less appropriate for intact savanna woodlands, where trees could be major obstacles during construction and disturbance of sodic soils for material could possibly increase erosion or gully initiation. Weed spread can also be an issue.

Along long scarp fronts of alluvial gullies, earth banks have been constructed to reduce diffuse runoff from flowing or seeping over scarps (Section 7.12; Figure 87a). Anecdotal information suggests they are successful at ponding shallow runoff and reducing headcut retreat rates. To maximise paddock utilization, they are often placed close to the scarp. However, direct rainfall erosion on the gully scarp (Shellberg et al. 2013a) and continued water seepage through the bank can continue headcut retreat. Ongoing scarp retreat can threaten the integrity of banks if they are situated too close to the scarp without appreciating future scarp retreat rates (Figure 87a).

Using dispersive or sodic soils to construct earthen banks can be problematic due to the high potential for soil piping to undermine or breach the bank (Figure 87b). This is especially true when overland runoff rates are high from upslope catchment areas and additional diversion/retention banks are not installed upslope to manage water (Figure 89). Piping and failure of earthen banks around gully scarps can be especially common when the slope of the bank(s) and subtle contours are not taken into account. Excess runoff can be diverted along the bank until a preferential flow or weak point in the bank is found, leading to piping and collapse (Figure 87b). Annual or periodic maintenance of earthen banks is needed to ensure their functionality over time (Figure 88b).

When earthen banks are used to divert rather than detain overland runoff, the discharge location needs to carefully identified and protected from erosion (Geyik 1986). Otherwise diverted water can initiate new gullies and just transfer the erosion problem from one location to another (e.g., Figure 88a; Figure 89). High resolution topographic mapping using LiDAR (e.g., Figure 40; Figure 83; Figure 99), in conjunction with field reconnaissance and surveys, will be useful in identifying appropriate locations, slopes, water flow paths and water discharge points. This will ensure that earthen banks actually reduce water runoff and erosion above gully heads, rather than locally accelerate it.

Installing water retention/diversion banks above alluvial gully headcuts will only partially reduce scarp retreat rates, as direct rainfall erosion and additional equilibrium slope processes with gullies might continue the erosion and retreat process regardless of water diversion (Shellberg et al. 2013a; 2013b). For example, a water diversion bank installed above an experimental gully (CRGC1-40), in conjunction with a full suite of gully treatments (battering, gypsum, revegetation, grade control), only partially reduced overall erosion rates. Reinitiation of headcutting in the gully from direct internal rainfall runoff continued the erosion process, albeit at rates 25% of that before treatment (Figure 98; Section 7.13.3).


a) b)

Figure 87 Mitchell catchment examples of earthen banks (berm or bunds) around the heads of gullies used to slow or divert water flowing into gully headcuts: a) earthen bank above an alluvial gully headcut on river frontage, b) an earthen bank around a road induced gully that has been breached by water seepage and piping through sodic soils.

a) b)

Figure 88 Functional examples of earthen banks (berm or bunds) around the heads of gullies to slow or divert water flowing into gully headcuts: a) a horseshoe earthen bank constructed along the perimeter of a gully headcut to divert road runoff, and b) a well maintained earthen bund in India above an alluvial gully headcut used to retain water runoff from an adjacent field.

Figure 89 A small earth bank (background) used to divert shallow overland runoff away from a headcut in the distance towards a safe disposal area and sedimentation pond to the left.

7.13 Complete Filling, Reshaping and Rehabilitation of Alluvial Gullies

7.13.1 Literature Review

For deeper gullies too large to plough, deep ripping, earth moving and landform regrading and resculpting using bulldozers or other machinery have been utilised frequently during engineering intervention in gullies. Often the goal is to reduce the average land slope by battering back the over-steepened sections of a gully (Gray and Sotir 1996). Slope reduction can decrease stream power in rills and gullies, but if the slope-length is increased providing greater fetch and water volume concentration, then changes to erosion can be marginal or worse. Alternatively if average slopes cannot be reduced, bench or step terracing has been used for agricultural protection and slope stabilization on steep hillslopes for thousands of years (Hudson 1987). This is conducted by effectively reducing local slopes and slope-lengths but maintaining average slopes.

Conventional regrading techniques using modern machinery have been extended to gully slope stabilization. Due to the operating expense of heavy machinery, these techniques are most often used when vital infrastructure is being threatened (e.g., roads, houses, dams) or when land reclamation is desirable from an agricultural or economic standpoint. For example, economic farming subsidies for wheat in the European Union have indirectly promoted the remoulding of silty-clay gully or badland slopes to increase agricultural land availability (Clarke and Rendell 2000). These engineering techniques can create dramatic changes to the landscape; however their success at actually reducing soil erosion is questionable. On many new slopes, rill, gully, and landslide erosion reinitiated soon after engineering works. By remoulding both erosional badland slopes and depositional fans into more uniform slopes with only seasonal vegetation cover, the projects effectively increased the slope-length and the connectivity of the hillslopes with downstream channels. Former depositional slopes at the base of badlands no longer buffered downstream reaches from sediment inputs, with resulting *net increases* in overall sediment yield (Clarke and Rendell 2000).

In less developed countries with greater human capital and demand for productive agricultural land, gully rehabilitation has been taken to a more intensive management level. For example in India along eroded alluvial soils in riverine riparian zones, the regrading and terracing of ravine or gully slopes is common to reclaim land for both agriculture and agroforestry (Prajapati et al. 1974; Haigh 1984; 1998; Yadav and Bhushan 1989; Bhusman et al. 1992; Narayan et al. 1999; Singh and Dubey 2000; Yadav et al. 2003). Most of the proactive reclamation for intensive agriculture is concentrated near the heads of gullies where existing fields are under threat from gully advancement. Yadav et al. (2003) documented the optimal size of small terrace plots on reclaimed land that could maximise rainfall infiltration and reduce water runoff, thereby reducing downslope plot soil erosion and downslope gully erosion. The reclamation of the more degraded and dissected ravine terrain closer to the river is more problematic, but even in this zone remnant knolls and hill tops are regraded using terracing and bunds for agriculture and agroforestry. Even gully beds are occasionally used for agriculture with the aid of check dams (Yadav and Bhushan 2002). Similarly in the Congo, Ndona and Truong (2005) also describe the complete regrading of a gully complex using slope terracing. Much of this extensive work was done with hand tools, with the goal of stabilizing slopes to protect infrastructure and improving the livelihoods of urban inhabitants.

In Australia, the complete regrading of gully networks has long been used as an engineering intervention (Stannard 1977; Boucher 1990; 1995; Mullavey 1991; Bartlett 1991; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008). Often, regrading has been conducted in concert with vegetation planting, chemical soil amendments, organic amendments such as compost, and improved stock control, such as during the creation of grassed waterways from incised gully networks (Stannard 1977; Pinkerton and Greentree 1991; QDERM 2004c). However in other cases, regrading is done as a one-off treatment by farmers or road maintenance crews with little design or insight from technical experts (Section 7.13.2). When regrading or soil ripping has occurred on dispersive soils without chemical amendments, adequate vegetative improvements, and stock control, gully channels and tunnel erosion have often reformed during the next wet season (Boucher 1990). The monitoring of gully slope regrading in Australia, and control for other influencing variables, has been insufficient to determine the long-term effectiveness of engineering attempts to create geomorphic stability, let alone a new geomorphic system in dynamic equilibrium (e.g., Mullavey 1991). Additional examples of gully regrading and engineering can be found in the grey-literature (Bartlett 1991; Lovett and Price 2006; Caitcheon 2007; Jenkins and McCaffrey 2008).

7.13.2 Case Study 9: Filling and Regrading Gully Slopes in the Mitchell Catchment

The lower Mitchell River and associated floodplains are a major area affected by alluvial gully erosion in northern Australia (Brooks et al. 2009; Shellberg 2011). In situations where large alluvial gully scarps have migrated over time towards road prisms, road crews have developed the practice of completely regrading gully head scarps with bulldozers, in the hope of stalling their advancement into roads. To date, these regrading efforts have not been conducted in association with any revegetation efforts, mulch or fertiliser application, chemical amelioration, or cattle exclusion. In most cases, newly shaped surfaces begin re-eroding via sheet flow and rilling almost immediately during the first wet season rains. After two wet seasons, deep rills often cut through the slope and new dendritic gully channels reform into the slope (Figure 90). Thus benefits to slope stabilization and sediment yield reduction remain highly unclear without other rehabilitation measures.

a) b)

Figure 90 Changes in gully head scarp morphology a) in 2007 following bulldozer regrading, and b) in 2009 after two wet seasons. Note the original head scarp in the background (before condition), the deep rills reforming gully channels in the foreground in 2009, and little vegetation cover on the slope surface.

Alluvial gully erosion can also threaten human infrastructure such as yards, sheds, houses, roads, fences, and airplane landing strips. In these cases, regrading and filling the gullies has been attempted. For example at Mount Mulgrave Station, a long section of gully scarp threatening the airplane landing strip was regraded, backfilled with a mixture of coarser alluvium (silt, sand, gravel) and revegetated with grass (Figure 91a). A small berm was constructed above the surrounding soil surface along the scarp front so as to reduce overland flow from pouring off the old scarp face. Since the scarp was located inside the air strip fence line, the re-established grass thrived due to reduced grazing pressure from periodic rotation and spelling (Figure 91ab). This combination of measures was successful at reducing scarp retreat over the last decade compared to the untreated raw scarp outside the fence line (Figure 91a bottom), which continued to erode at an average rate of 0.13 m/yr over 50 years, with maximum rates up to 1.4 m/yr (Shellberg 2011).

The placement of old tyres in the gully bottom and at the head scarp in isolation of the other measures above was not effective at reducing scarp retreat and could have accelerated it in places (see Section 7.10.1; Figure 65).


a) b)

Figure 91 a) Oblique aerial view of a gully head scarp at Mount Mulgrave next to the air strip fence line (in black) in Feb-2010. The dark green vegetated patch within the air strip (top middle right) is where the gully front was regraded, backfilled with coarser material, revegetated with grass, and only lightly grazed in rotation. b) Ground view in Oct-2008 of the regraded section of gully scarp.

At another gully scarp at Mount Mulgrave, a steep scarp face was backfilled with many tonnes of sand and gravel originating from the annual cleaning of the local river causeway (Figure 92a). Preliminary observations after one wet season indicated that most of the sand is still in place, but that several areas of sub-surface water sapping and slumping of the sand face exist at the new graded scarp face. While the sand fill was partially colonised by native *Acacia spp.* shrubs, it was also colonised with several noxious exotic weeds from the river such as sicklepod (*Senna obtusifolia*) and noogoora burr (*Xanthium pungens*) and others (Figure 92b). Establishing grass vegetation on the well-drained and nutrient poor sand will be difficult. Similar to earlier efforts at Mount Mulgrave, it could be beneficial to mix sand into the native silt soils to produce a sandy loam that could be proactively revegetated with native or exotic grass and trees, rather than just weeds and shrubs from the river.


a) b)

Figure 92 a) Oblique aerial view of a gully head scarp at Mount Mulgrave that has been backfilled with local river sand in an attempt to slow erosion into the road in the background. Note the original scarp front remains intact in the right side of the photo. b) Colonization of the river sand by native Acacia spp. and exotic weeds like sicklepod (*Senna obtusifolia*).

7.13.3 Case Study 10: Regrading Alluvial Gully Slopes along Main Roads in the Normanby Catchment

Both historically and currently along most roads in the Normanby catchment (and Cape York Peninsula), battered slopes along road edges generally have not been rehabilitated with vegetation, chemical, or organic amendments to promote long-term stability and reduce sediment erosion (e.g., Figure 93a). Most often these slopes are left to revegetate passively over time. Severe reinitiation of rill and gully erosion of these slopes is often the result, especially on dispersive or sodic soils. By learning from these lessons, management efforts are increasingly being made to rehabilitate or stabilise these slopes with vegetation, matting, and/or rock (e.g., Figure 93b; Figure 94; Figure 95). Both successes and failures are common.


a) b)

Figure 93 Normanby road batters a) raw without any intervention ready to re-erode and b) using geotextile fabric for stabilisation.

For example, along the road approach to the old West Normanby bridge crossing, some rehabilitation efforts were made to stabilise severe gully slopes during the road abandonment process after the new bridge was built. One side of the road approach was battered off by bulldozer, capped with coarser non-sodic soils, sown with grass seeds, and mulched with hay (Annette Marriott personal communication). The other side of the road approach was left as an intact gully scarp. Five (5+) years later, dramatic vegetation differences can be seen between the different sides (Figure 94). While some of the originally planted grass (e.g., *Urochloa mosambicensis; Chloris gayana*) still exists, much of the battered slope has also been colonised by weeds such as grader grass (*Themeda quadrivalvis*) and mintweed (*Hyptis suaveolens*). Some of the vegetation success of the site can also be attributed to its partial isolation from cattle grazing due to its location in the corner of an isolated paddock where cattle do not concentrate. Regardless, the right (north) approach slope is dramatically more stable with less erosion than the left (south) approach slope.

Figure 94 Comparison between the left and right approaches to the south side of the old West Normanby bridge crossing, April 2012. The right side was battered back and revegetated during the decommissioning of the road crossing circa 2006. Note that significant erosion continues down the centre of the old road due to excess water runoff.

In another example of recent proactive stabilization of sodic soils along roads, road batters along the Peninsula Development Road between Lakeland and Laura have been armoured with angular gravel from nearby rock quarries. By covering the sodic soils with rock amour, rill and gully erosion of the steepened slope can be minimised. Armouring the toe of the slope with rock, along with periodic rock grade-control structures, can also prevent incision of the road ditch, lowering of the base level, and reactivation of rill and gully erosion (Figure 95a). Compared to adjacent road slopes that are riddled with rills and gullies (Figure 95b), the influence of the rock armouring can be dramatic. The biggest challenge for using this approach to gully stabilization is the need for an abundant local source of angular gravel to cover large areas, which can problematic and economically prohibitive for gully stabilization projects away from main roads.

a) b)

Figure 95 Road batter stabilisation using a) angular gravel armouring on battered slopes of sodic soils and alluvial gullies along the Peninsula Development Road (PDR), and b) a comparison between a raw alluvial gully and a battered rock armoured gully with toe protection.

7.13.4 Case Study 11: Complete Intensive Gully Treatment at CRGC1-40

In the Normanby catchment, a full set of physical, chemical and biological rehabilitation treatments was applied to one gully lobe (CRGC1-40; Figure 97a; Figure 99) of a large alluvial gully complex (CRGC1; Figure 96). Several nearby gully lobes were kept as controls (CRGC1-32,39), while others were just treated with physical structures (e.g., rock/wood grade control CRGC1-33-34) or just physically battered (CRGC24) (Table 6; Figure 99). In two other nearby gully lobes (CRGC1-29, CRGC60/61), a more detailed experiment on different combinations of chemical and biological treatments was studied after full battering of slopes to different angles (see Section 7.13.5). The "all" treatment at CRGC1-40 represents the end member of proactive treatments using direct/intensive intervention with sodic soil rehabilitation, but without the next expensive step of completely burying the gully and sodic soils with rock or imported fill and non-sodic topsoil.

Figure 96 Oblique photo of CRGC1 before project implementation in Nov-2011.

At CRGC1-40 (Figure 96; Figure 99), the 0.2 ha gully lobe was initially infilled and battered back to a more stable angle using an excavator in Dec 2011 (Figure 97bc). The soil material for infilling and battering came from the local gully walls, which consisted of ~ 50cm of dispersive non-sodic silt soil, overlaying 3m of sodic clay soils (Figure 103). These layers were fully mixed together during excavation (Figure 97b) to attempt remediation of fully sodic soils more typical for profiles in the region, rather than trying to retain the topsoil layer for later surface spreading. Note that in other situations retaining the topsoil for later surface use would be a preferred alternative, but only if sufficient volumes could be obtained.

After battering, the surface soils were treated with the equivalent of 70 t/ha gypsum ($CaSO_4$ $2H_20$) (Figure 97d). This mass was required to treat the top 0.5 m of mixed sodic soil to reduce the average exchangeable sodium percentage (ESP) value from ~ 50 to 5 ESP. The gypsum application rate was estimated from initial down profile measurements of exchangeable sodium percentage (ESP) (Figure 103), cation exchange capacity (CEC), electrical conductivity (EC) and bulk density following calculation methods and models in Nelson et al. (2000) and Coventry (2004).

Wood check dams consisting of small to moderate sized woody debris from the nearby cleared paddock were installed as grade control structures down the longitudinal profile of the reshaped gully in order to reduce overland flow velocity and trap water and sediment (Figure 97ef). These wood structures were placed in 0.5m shallow trenches and pressed into place with an excavator. They were oriented in a slightly concave pattern directed upslope. Furthermore at the top of the swale and reshaped gully, a wood check dam and berm were installed to reduce any excess overland flow from entering the new swale from the uneroded upslope catchment area in the paddock. Therefore most of the new erosive power would come directly from rainfall.

Subsequently, the entire surface was hydromulched for revegetation (Figure 97f). The hydromulch mix consisted of exotic Indian blue grass (*Bothriochloa pertusa*), sabi grass (*Urochloa mosambicensis*), Japanese millet (*Echinochloa esculenta*), verano stylo (*Stylosanthes hamata*), fertiliser (N-P-K = 12-5-14), envirotak and curosol tackifiers, paper, bagasse, and an extra 10 tonnes/ha gypsum (Table 5). Due to initially high grazing pressure in the paddock, the 0.2 ha gully was fenced to exclude stock.

The newly shaped gully surface was surveyed in detail with terrestrial laser scanning (TLS) (Faro 3-D) soon after hydromulching but before vegetation regrowth, to precisely measure the 3-D surface elevations in order to document re-erosion into the future. The site was resurveyed in Nov-2012 and May 2013.

The reshaped and hydromulched gully experienced initially slow but eventually vigorous grass growth through the 2012 wet season (Figure 97ghi). The wood weirs performed well to retain water and sediment (Figure 97h). Rilling was minimal on the slopes of the new swale due to good grass cover and improved infiltration into the soils with gypsum. However within the bottom of the new swale, shallow rilling and head-cutting from the bottom up (base-level control) initiated channel rejuvenation after early rains, putting the lower wood structures at potential future risk of failure (Figure 97ghj). In hindsight, the spacing of the grade control structures could have been increased, as well as the height and depth of the structures. Rock could have also been used to a greater depth to prevent undermining. However overall, the “full” treatment with physical, chemical, and biological measures performed better than other nearby treatments that were lacking one or more stabilization tools.

From repeat airborne LiDAR measurement in 2009 and 2011 (1m^2 pixels), it was estimated that 26.6 tonnes/year of sediment eroded from the gully lobe of CRGC1-40 (30.8 m^3 over two years, soil bulk density of 1.73 tonnes/m^3). Most of the measured erosion was concentrated at the headcut (Figure 99), but these data are likely a minimum since more subtle changes below the resolution detection limit of airborne LiDAR were not measured. In comparison using higher resolution TLS surveys over the WY 2012 wet season, 14.8 tonnes/year eroded from CRGC1-40, while 4.9 tonnes/year deposited, for a net erosion of 9.9 tonnes/year (18.8 kg/m^2/yr). Over the WY 2013 wet season, 2.6 tonnes/year eroded from CRGC1-40, while 4.1 tonnes/year deposited, for a net *deposition* of +2.6 tonnes/year (+5.1 kg/m^2/yr). These data were obtained after masking out zones of known error along TLS survey margins and masking out change within wood structures and dense vegetation growth. However, despite mowing the grass in May 2013 before surveying, it was difficult to remove the influence of the grass stubble growth. Thus, the net deposition during WY 2013 could have been partially influenced by grass. Additional surveys at the end of the dry season 2013 will be needed to confirm results.

While these data were collected by two different LiDAR/TLS techniques (airborne and terrestrial) at different scales and under different annual rainfall conditions, they do suggest that erosion decreased significantly as a result of the full suite of treatments after the first year, and resulted in net sediment deposition by the second year. However, erosion and reinitiation of headcuts was not eliminated due to treatment, it was only slowed. Headcutting will continue to some degree at this site over time, and should be monitored.

The total cost of this direct/intensive treatment was $6000 for 0.2 ha, which included equipment hire and labour, gypsum, hydromulch, and fencing. This does not include monitoring costs.

a) b)

c) d)

e) f)

g) h)

i) j)

Figure 97 Sequential photographs of treatments at Gully 40 at CRGC1 a) before reshaping in Nov-2011, b) at the beginning of gully battering in Dec-2011, c) toward the end of gully battering in Dec-2011, d) during the addition of gypsum ($CaSO_4$) in Dec-2011, e) after wood check dams and gypsum addition in Dec-2011, f) during hydromulching in Dec-2011, g) during headcut reinitiation in Jan-2012, h) during a rainstorm with water/sediment retention behind wood check dams in Jan-2012, i) after grass and weed (*Hyptis suaveolens*) vegetation growth in April-2012, and j) after an extended dry season new wet season rains in Jan-2013 with modest grass cover but new growth emerging.

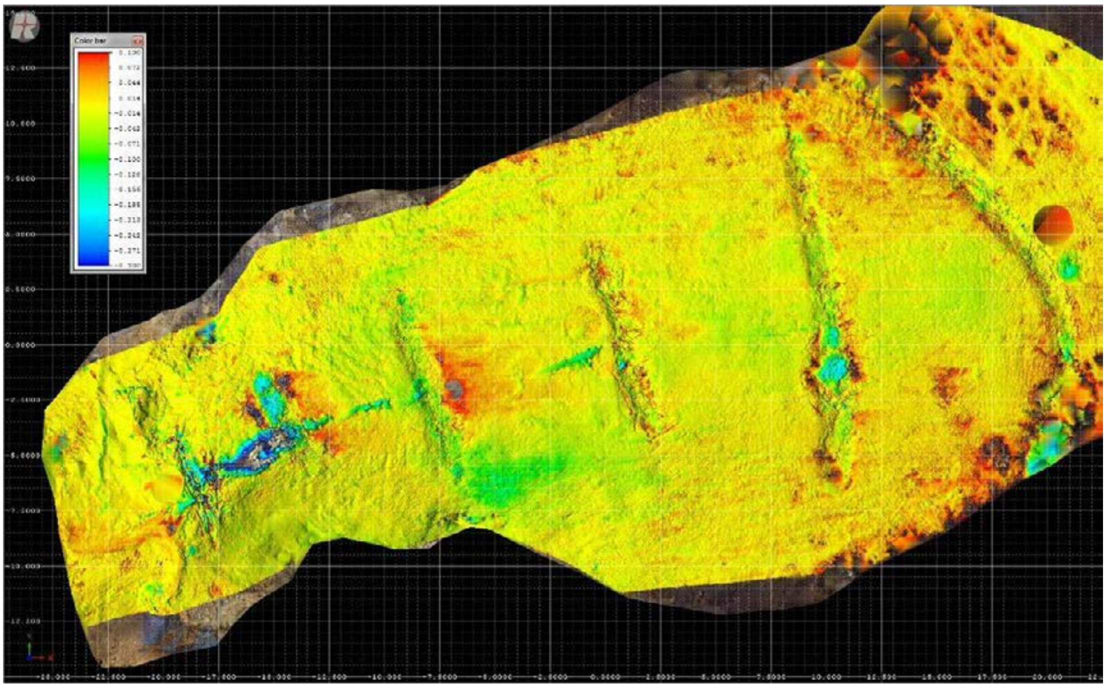


Figure 98 Terrestrial laser scanning (TLS) difference data of changes in ground elevation (erosion = blue; deposition= red) over the water year (WY) 2012 wet season (December 2011 to November 2012) at CRGC1-40 following full treatment (gully reshaping, gypsum, hydromulching, wood weir addition). Note water flow is from right to left, gully head-cutting on the bottom slope, sediment deposition upstream of wood weirs, pig rooting in the second to top wood weir, and dark red vegetation patches in the eastern sections that were filtered from the final dataset.

7.13.5 Case Study 12: Experimental Trials of Different Biological and Chemical Treatments of Regraded Slopes at CRGC1-29 and CRGC60/61

7.13.5.1 Introduction

Can alluvial gullies and sodic sub-soils in northern Australia be rehabilitated in-situ with physical, biological and chemical amendments to improve stabilization and long term grass growth? This was a key question that needed to be answered for gullies in the Normanby catchment and beyond. Results from CRGC1-40 above (Figure 97; Section 7.13.4) helped address this question, but more detailed plot scale trials were also implemented at neighbouring CRGC1-29. From other examples of sodic soil and gully stabilization, it is clear that sodic soil slopes and gullies could be partially stabilised by either fully armouring them with a rock blanket (Figure 95) or completely burying them with some other topsoil and revegetating (Figure 91; Figure 92; Figure 94). However, relying on large volumes of imported rock and soil material would be impractical at remote sites. Using native soils in situ with more targeted additions of soil amendments might be more practical and sustainable, but still could be cost limiting at remote or non-strategic sites.

7.13.5.2 Methods

Physical Treatment and BACI study design

On Crocodile Station, two gully slopes in two different gully complexes were chosen as sites for experimental plots. Both gullies CRGC1-29 (Figure 22; Figure 96) and CRGC60-61 (Figure 45) are located in a large cleared paddock on alluvial textural-contrast soils with high levels of exchangeable sodium percentage (ESP>>5) at depth.

At CRGC1-29 (left side of Figure 96; Figure 99), a 50 m long gully side wall was regraded using a bulldozer to create a relatively uniform slope (12% mean, range 11.25 to 13.25%) with a slope-length of 25m. The entire gully profile from the surface to up to 3m deep was thoroughly mixed laterally and vertically via deep ripping and bulldozing so as to create a uniform soil volume that was representative of average sodic sub-surface soils that the gullies were eroding into (Figure 100). There generally were insufficient volumes of non-sodic topsoil (<50cm) to spread over any battered gully slopes, unless topsoil was scraped and borrowed off large areas of the adjacent uneroded paddock to cover gully sub-soils. Thus, locally remaining non-sodic surface soils were mixed and diluted into the much more voluminous sodic sub-soils. The result is representative of the more typical alluvial gully situation in the Normanby catchment where non-sodic surface soils are fairly thin to absent.

This physically battered slope was used to set up 7 experimental plots (7m x 25m) with different biological and chemical treatments to increase the resistance of sodic gully soils to erosion (Figure 101). The original gully sidewall lacked any potential of surface overland runoff from the surrounding paddock due to land sloping away from the original gully scarp; hence erosion was entirely driven by direct rainfall and resulting runoff (Figure 99).

An additional gully sidewall was similarly regraded at CRGC60/61 for experimental plot treatment (Figure 45), but with a reduced slope length of 12m but generally similar plot slopes (13% mean, range 11.5 to 14 %). Here, the non-sodic surface soils had already been removed via gully erosion, leaving scalded sub-soils armoured with ferricrete nodules. This surface was ripped with a bulldozer to a depth of 1.0m and then regraded for experimental plot treatment.

At CRGC1, two additional gullies were left intact, un-battered, and un-treated (CRGC1-28 and CRGC1-32), which were surveyed and used as erosion controls to battered plots.

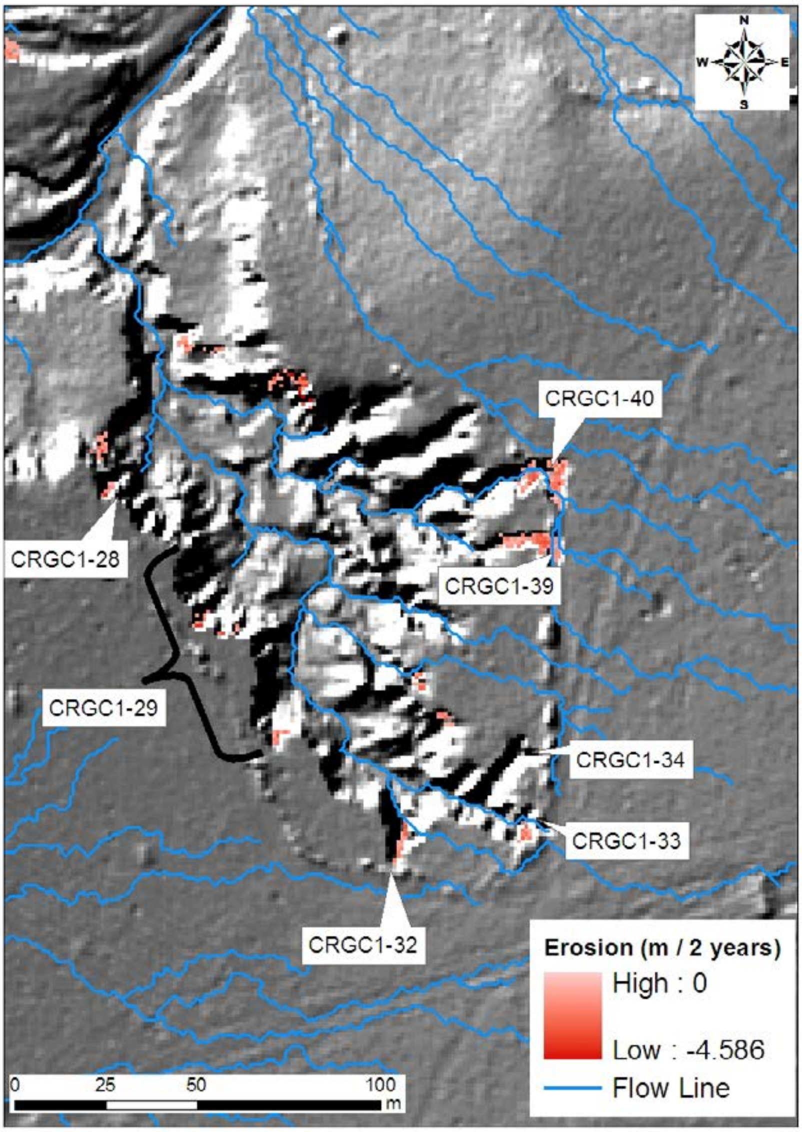


Figure 99 Airborne LiDAR hillshade map ($1m^2$ pixels) of CRGC1, and the length of gully slope at CRGC1-29 regraded for experimental analysis. Note that no surface flow enters CRGC1-29 from the surrounding floodplain hillslope, since water flows away from the scarp edge.

At CRGC1-29, seven (7) experimental plots 7 m wide by 25 m long by 12% slope were established following a before-after control-impact (BACI) design (Underwood 1994a; 1994b; Smith 2002) with the following treatments and controls (Figure 100; Figure 101):

1. No Treatment
    - Status quo, highly sodic, infertile silty clay soils
2. Gypsum, Compost, Native Grass
    - ~80t/ha gypsum; 25mm surface compost; Native grass: Kangaroo (*Themeda triandra*), Black spear (*Heteropogon contortus*), Queensland bluegrass (Dichanthium sericeum) (180 kg/ha or 3.8 kg/210 m^2)
3. Gypsum, Compost, Exotic Grass
    - ~80t/ha gypsum; 25mm surface compost; Exotic grass: Indian bluegrass (*Bothriochloa pertusa*), Saraji Sabi grass (*Urochloa mosambicensis*), Jap millet (*Echinochloa esculenta*) (180 kg/ha or 3.8 kg/210 m^2)
4. Gypsum, Hydromulch, Exotic Grass
    - ~90t/ha gypsum; 25mm surface compost; Exotic grass: Indian bluegrass (*Bothriochloa pertusa*), Saraji Sabi grass (*Urochloa mosambicensis*), Jap millet (*Echinochloa esculenta*), verano stylo (*Stylosanthes hamata*) (100 kg/ha 2.1 kg/210 m^2)
5. Gypsum Only
    - ~80t/ha gypsum
6. Compost, Native Grass
    - 25mm surface compost; Native grass: Kangaroo (*Themeda triandra*), Black spear (*Heteropogon contortus*), Queensland bluegrass (Dichanthium sericeum) (180 kg/ha or 3.8 kg/210 m^2)
7. Straw, Exotic Grass
    - 25mm surface straw; Exotic grass: Indian bluegrass (*Bothriochloa pertusa*), Saraji Sabi grass (*Urochloa mosambicensis*), Jap millet (*Echinochloa esculenta*) (180 kg/ha or 3.8 kg/210 m^2)

Similarly, at CRGC60/61, five (5) experimental plots 5 m wide by 12 m long by 13% slope were established with the following treatments and controls (Figure 102):

1. No Treatment
    - Status quo, highly sodic, infertile silty clay soils
2. Straw, Exotic Grass
    - 25mm surface straw; Exotic grass: Indian bluegrass (*Bothriochloa pertusa*), Saraji Sabi grass (*Urochloa mosambicensis*), Jap millet (*Echinochloa esculenta*) (180 kg/ha or 1.4 kg/75 m^2)
3. Gypsum Only
    - ~80t/ha gypsum
4. Gypsum, Compost, Exotic Grass
    - ~80t/ha gypsum; 25mm surface compost; Exotic grass: Indian bluegrass (*Bothriochloa pertusa*), Saraji Sabi grass (*Urochloa mosambicensis*), Jap millet (*Echinochloa esculenta*) (180 kg/ha or 1.4 kg/75 m^2)
5. Gypsum, Compost, Native Grass
    - ~80t/ha gypsum, 25mm surface compost; Native grass: Kangaroo (*Themeda triandra*), Black spear (*Heteropogon contortus*), Queensland bluegrass (Dichanthium sericeum) (180 kg/ha or 1.4 kg/75 m^2)


Bushnell
11-30-2011 08:00:57

a)


Bushnell
12-01-2011 15:28:38

b)


Bushnell
12-11-2011 11:00:02

c)


Bushnell
12-14-2011 10:51:44

d)


Bushnell
12-20-2011 11:00:07

e)


Bushnell
01-12-2012 08:27:10

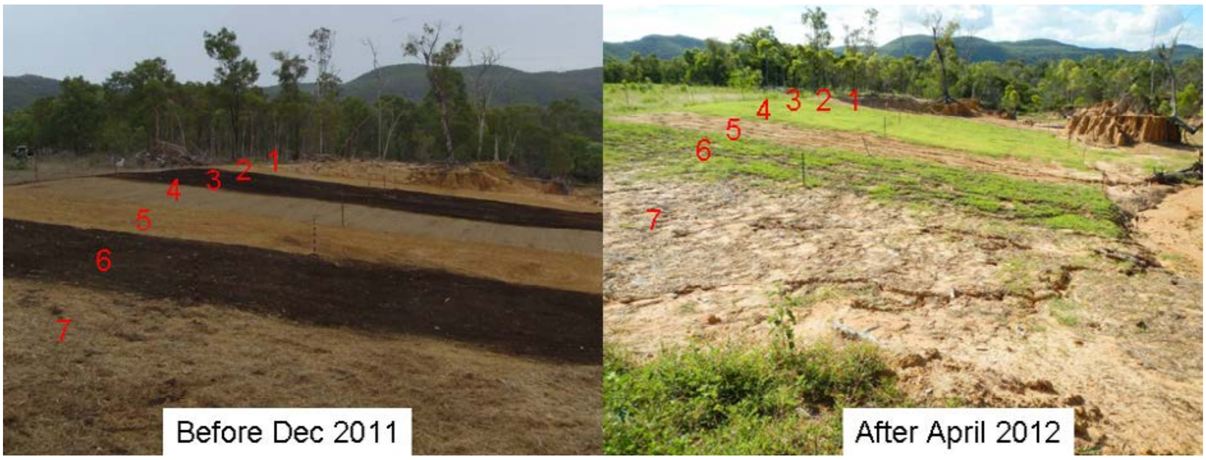
f)

g)

h)

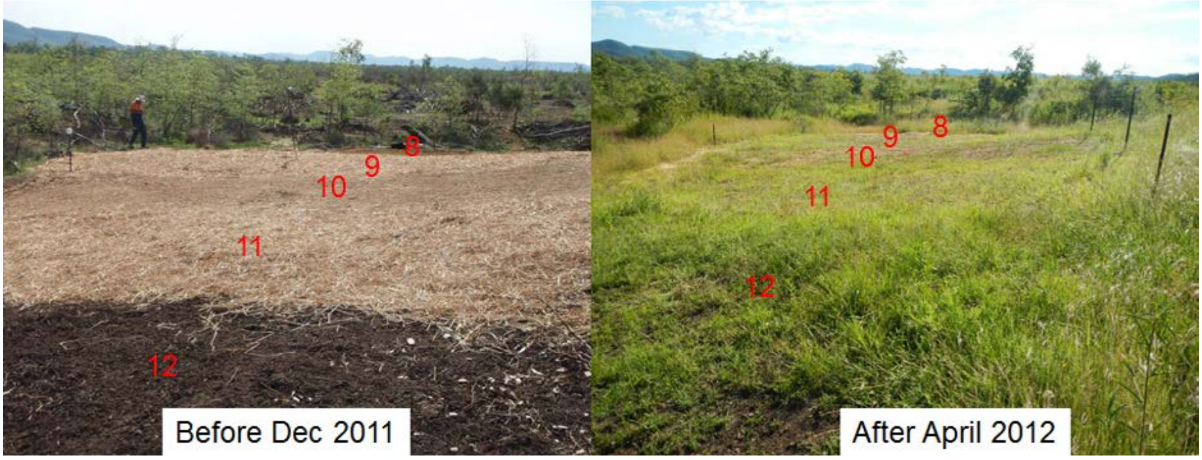
i)

Figure 100 Sequential photographs of CRGC1-29 a) Plots 1 to 3 before reshaping, b) Plots 1 to 3 during reshaping, c) Plots 1 to 3 after reshaping and gypsum addition, d) Plots 1 to 3 during compost spreading, e) Plots 1 to 3 after compost and grass seeding, f) Plots 1 to 3 after initial grass sprouting and rilling during early rainstorms, g) Plots 1 to 7 after the end of the wet season in March 2012 with some grazing by cattle and wallabies and rill erosion, h) Plots 1 to 7 after the end of an extended dry season in January 2013 with significant desiccation of perennial vegetation, and i) Plots 1 to 7 after the end of the wet season in April 2013.



a) b)

Figure 101 Side view of the seven (7) different treatment and control plots at CRGC1-29 before (a) and after (b) the 2011/12 wet season.



a) b)

Figure 102 Side view of the five (5) different treatment and control plots at CRGC60/61 before (a) and after (b) the 2011/12 wet season.

<u>Soil Chemical Treatment and Analysis</u>

For chemical analysis of sodic soils, analytical procedures for the Exchangeable Sodium Percentage (ESP) of gully soils followed methods 15C1 or 15A2 in Rayment and Higginson (1992). When soils had a pH < 7.3, method 15A2 was used (1M ammonium chloride at pH 7.0) with a pre-treatment for soluble salts using ethanol/glycerol. When the pH > 7.4, method 15C1 was used (1M ammonium chloride at pH 8.5) with a pre-treatment for soluble salts using ethanol/glycerol. Use of ammonium chloride as an extractant was preferential since ammonium acetate can dissolve solid phase salts in calcareous and gypsiferous soils (Rayment and Higginson 1992).

Initial measurements of the Exchangeable Sodium Percentage (ESP) of the sub-soils ranged from 40 to 60% in November 2011 (Figure 103). Gypsum was applied to the soil surface to replace exchangeable sodium (Na^+) with calcium (Ca^{+2}) on clay particle exchange sites, reduce clay swelling and aggregate dispersion, reduce crust formation and soil surface sealing, and in turn increase soil permeability, hydraulic conductivity and field infiltration rates of surface rainwater (Keren 1996; Graber et al. 2006). Gypsum application rates were determined from calculations of how much gypsum ($CaSO_4$) would need to be applied to reduce the ESP from current levels to under 5% for the top 50 cm of soil volume of the mixed and battered soil profile (Nelson et al. 2000 and Coventry 2004). This resulted in a large application rate of ~80t/ha of minus 2 mm gypsum, which is a typical maximum for application to highly sodic soils (Naidu et al. 1995; Coventry 2004). On specific treatment plots, gypsum was applied uniformly across the surface and then turned into the top 5-10 cm of soil using a machine leveller (Figure 100c). Treatment of deeper soils was presumed to occur in the future via downward movement of dissolved calcium.

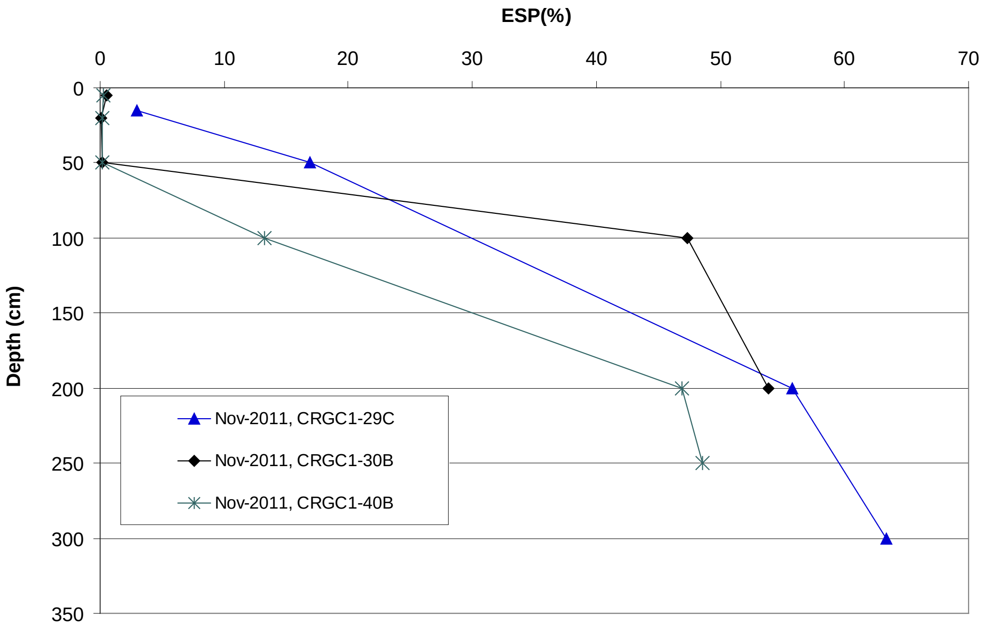


Figure 103 Initial soil profiles of Exchangeable Sodium Percentage (ESP) with depth at CRGC1 in Nov-2011.

A more complete suite of soil chemistry conditions was also assessed before gully regrading, after treatment application but before the wet season, and after the 2011/12 wet season. Soil chemical analysis included: pH and EC (1:5 water); exchangeable Sodium, Potassium, Calcium, Magnesium, Hydrogen, Aluminium, Cation Exchange Capacity (CEC), Exchangeable Sodium Percentage (ESP); available Calcium, Magnesium, Potassium, Ammonium, Nitrate, Phosphate, Sulphur; Bray I and II Phosphorus; Colwell Phosphorus; available Micronutrients Zinc, Manganese, Iron, Copper, Boron, Silicon; Total Carbon (TC), Total Nitrogen (TN), Organic Matter, TC/TN Ratio. The chemical nature of the compost and straw was also assessed. For this report, analysis of results focused on soil exchangeable sodium percentage (ESP) and exchangeable magnesium percentage (ESM), but other metrics will also be indicative of soil changes over time with treatments.

Mulch Treatment and Analysis

Compost and straw mulch were applied 25 mm thick over the soil at specific treatment plots in order to reduce the direct raindrop impact on surface soils, retain soil moisture, and in the case of the compost, to add organic matter and nutrients to the soil for a better vegetation growing medium (Figure 100d). This material was acquired from a nearby farm at Lakeland. The effectiveness of these mulch treatments was assessed qualitatively using photographic observations and quantitatively using repeat topographic surveys with terrestrial laser scanning (TLS, see below).

Vegetation Treatment and Analysis

Both native and exotic grass seed were sown by hand directly onto the mulch or soil surface of specific treatment plots. Where grass seed was sown over mulch, the seed was mixed into the soil and mulch using steel rakes in order to cover the seed by 10-20 mm of soil and mulch for best germination conditions. High sowing rates were used for both native and exotic seeds to ensure good grass cover and germination rates (up to 180 kg/ha; ~ 3.8 kg/210 m^2). These rates are similar to sowing densities at mine rehabilitation sites but much lower than for typical pasture sowing. Where hydromulching was used, a lower sowing density was applied due to a more even seed distribution in the mulch mix and multiple application layers in the bonded fibre matrix (BFM).

The native grass seed mix included Kangaroo (*Themeda triandra*), Black spear (*Heteropogon contortus*), and Queensland bluegrass (*Dichanthium sericeum*), with the two former grasses being the common and dominant native grasses in the upper Normanby catchment on high stream banks and terraces before exotic species were introduced (Weston 1988; Partridge 1995; Neldner et al. 1997; Crowley and Garnett 1998, 2000). The exotic grass seed mix included Sabi (*Urochloa mosambicensis var Saraji*), Indian blue grass (*Bothriochloa pertusa var Dawson*), and Japanese Millet (*Echinochloa frumentaceae*), with the former two stoloniferous grasses being used commonly in mine site and degraded pasture rehabilitation (Pressland et al. 1988) and the later as an annual for quick germination and cover generation.

Hydromulching application used typical commercial rates of the following mix (Table 5) of exotic grasses (total 100 kg/ha) of hulled and unhulled Indian Bluegrass (*Bothriochloa pertusa*), Sabi (*Urochloa mosambicensis*), Japanese Millet (*Echinochloa frumentaceae*), Verano Stylo (*Stylosanthes hamata*), plus starter fertiliser (250kg/ha; 12-5-14 N-P-K), curosol (120 L/ha), envirotak (30 kg/ha), paper (1,500 kg/ha), and bagasse (4,500 kg/ha). In addition to the 80/t/ha of -2 mm gypsum originally applied to the hydromulch site, a further 10 t/ha of fine gypsum (5 µm Gypflo) was applied with the hydromulch water mix, which resulted in more readily available and active gypsum reactions with the soil. The hydromulch was applied in two layers to ensure proper binding with the soil and full coverage (i.e., bonded fibre matrix, BFM).

Vegetation conditions at each experimental plot were assessed using two (2) permanent monitoring points at each plot during April and November of each year of the study period, and into the future. A 2x2 m grid (4 m^2) was placed around each monitoring point. Semi-quantitative measurements were made of the pasture ground vegetation conditions including aerial projected % cover of all organic material, % cover of just perennial grass, # of species, # of perennial tussocks, estimate of pasture yield (standing biomass) from visual picture standards, grass and weed species' dominance, soil condition, and overall land condition rating (see Appendix 10.1 and 10.2).

Grass root biomass, plant height, and above ground biomass were measured for 16 native and exotic plant species at Plots 2 and 3, which were treated with gypsum and compost for similar growing environments. For each plant, a 75 mm tube core was driven 14 cm deep into the central tussock of identified grass species. Above ground plant biomass was separated from root biomass and soil. Soil was washed from roots through a 63 µm sieve and roots were picked, dried and weighted for comparison between species.

Soil Physical Analysis

The physical bulk density of the soil was measured before gully regrading (Nov-2011), after treatment application but before the wet season (late Dec-2011), and after the wet season (June 2012). Duplicate bulk density samples were collected at each experimental plot, at in-situ undisturbed gully sub-soils along a vertical profile, on undisturbed well-vegetated surface soils in the adjacent paddock, and stripped and scalded paddock surfaces. Surface organic material was removed from the immediate soil surface before bulk density samples were collected, so as to assess the bulk of near surface soils.

The particle size distributions of soils before and after treatment were measured using a Malvern Mastersizer 2000 on sub-samples before and after mechanical dispersion. However these particle size results are still pending and are unavailable for this report.

Water infiltration rates into the soil at each experimental plot were measured using a double ring infiltrometer (Figure 104a; ASTM 2009) during the dry season (Aug-Sept 2012) after the first wet season. Two rings were driven into the soil without disturbing the soil surface and cover. The inner ring was driven ~100 mm deep, while the outer ring was driven ~150-200 mm deep, which promoted one-dimension vertical flow beneath the inner ring. A falling head test was used due to low infiltration rates that took 3-5 days per measurement site in a remote field location, and because of the inability to use automatic pressure transducers inside a sealed Mariotte tube (ASTM 2009). Rather, water levels were recorded in the inner and outer rings of the infiltrometer every 5 minutes during the test periods using continuous stage recorders (pressure transducers). Rings were covered with plastic film with breather holes to reduce evaporation, along with a shade canopy over the entire infiltration setup (Figure 104b). Water level measurements were also made in an adjacent water container that served as a 'dummy' control without infiltration but with similar evaporation conditions as the infiltrometer. These evaporation data were used to correct data in the infiltrometer to obtain NET infiltration rates. Manual backup data were also collected in connected but unsealed Mariotte tubes (ASTM 2009). For one measurement site per experimental plot location, the average infiltration rate (mm/day) was calculated for both 3- and 5-day periods, corrected for local evaporation measurements.


a) b)

Figure 104 Infiltration measurement setup showing a) the inner and outer measurement rings, and b) the full infiltration measurement setup.

Rainfall and Runoff Analysis

Rainfall was measured at CRGC1 during the study period (2011-2013) using an automated tipping bucket (0.2mm per tip) to assess rainfall intensity duration and magnitude at the event, daily and annual scales. Runoff data was not measured at the plot scale due to the lack of collection infrastructure. Runoff data were collected at the outlet of the entire

CRGC1 gully (Figure 96) using a continuous stage recorder and periodic discharge measurements, but the data are not specific enough for plot scale analysis. Rather, runoff at the plot scale was qualitatively assessed using time-lapse photography that collected at least one picture per day, with additional major events periodically captured using motion detect technology.

Soil Erosion Volume Analysis

Soil erosion and deposition volumes on different treatment and control plots over two wet season(s) were measured using ground-based terrestrial laser scanning (TLS) of the soil surface elevation (Heritage and Hetherington 2007). A Faro 3-D laser scanner was used to survey hundreds of thousands of points across different plot surfaces, with point spacing less than 100mm. At CRGC1-29 plots and control gully surfaces at RGC1-28 and CRGC1-32, detailed TLS surveys were conducted immediately after plot and treatment application in December 2011, and sites were resurveyed in November 2012 and May 2013 to assess annual erosion volumes per plot. CRGC60/61 plots were only surveyed in December 2011 and November 2012.

Using ArcGIS 10.1, these TLS point data were used to create a TIN (triangulated irregular network), from which a raster DEM (digital elevation model) was generated with 5 mm pixels. Raster DEMs for different time periods were subtracted to calculate vertical change (erosion or deposition). Changes at all pixels within each defined plot boundary were totalled to calculate gross erosion and deposition, as well as net erosion volumes for the plot (erosion minus deposition). Volumetric estimates of erosion and deposition were converted to mass (tonnes) using bulk density measurements. The pattern, density, and depth of rilling will also be measured using this technology, but is not reported here.

For bare gully soil surfaces, the original TLS raw survey data were used for DEM creation. Surveying in November and December of 2011 and 2012 reduced the potential for grass growth to influence survey results, due to dry and desiccated conditions with little grass cover (Figure 100h). Surveys in May 2013 had more abundant grass growth (Figure 100i), but this grass was mowed in plots before surveying and grass clippings were caught and removed in a lawnmower basket. However, remaining grass stubble could have influenced survey results. In addition, plots initially covered with straw in November 2011 could have also influenced survey results through elevated erosion changes as straw decomposed (Plot 7, Figure 101; Plots 9 and 11, Figure 102). The surface of compost material was deemed equivalent to the soil surface (Figure 100ef). For grass stubble and straw situations, additional TLS data filtering was conducted using 50mm and 100mm vertical thresholds to find the lowest elevation points within various search radii. In some cases this grass or straw material could not be filtered due to dense coverage low to the ground surface. Therefore, calculated erosion volume changes in these situations could result in error in either the positive (straw increasing initial elevations) or negative (grass stubble growth causing apparent deposition) direction. These errors were most pronounced during May 2013 survey when grass stubble was present. Resurveying plots in November 2013 could reduce these errors.

7.13.5.3 Results

Rainfall

Annual rainfall at Crocodile Station during WY 2012 (786 mm) was 85% of normal for the region (928 mm at Laura Post Office 1897-2012). There were no major falls with daily totals greater than 60 mm (Figure 105). Despite an average Dec-2011 rainfall total, establishment and growth of grass species following 15-Dec sowing was slow. Poor initial establishment was also influenced by a two week period in early Jan-2012 without rainfall. However, after mid-January rainfall conditions became conducive to vigorous grass growth that continued into Apr-2012. While total rainfall was less than normal, rainfall patterns were well dispersed throughout the wet season.

For WY 2013, rainfall patterns were highly erratic with an abnormal wet season. Rainfall was 20% to 60% of normal for Nov and Dec-2012, with an extremely slow start to the wet season. The wet season did not begin until the 16th of Jan-2013 with the onset of ex-tropical cyclone Oswald crossing the Normanby catchment, when 400 mm of rain fell over 10 days, with consistent but not extremely heavy rainfall (Figure 105). A 1-in-12 year recurrence interval flood event occurred on the Laura River as a result of Oswald. Following this event, the month of Feb-2013 experienced low rainfall, 20% to 60% of normal, resulting in poor regional grass growing conditions. However, the monsoon returned in March 2013 with 60-100% of normal rainfall. Total rainfall for WY 2013 (741 mm) was 80% of normal.

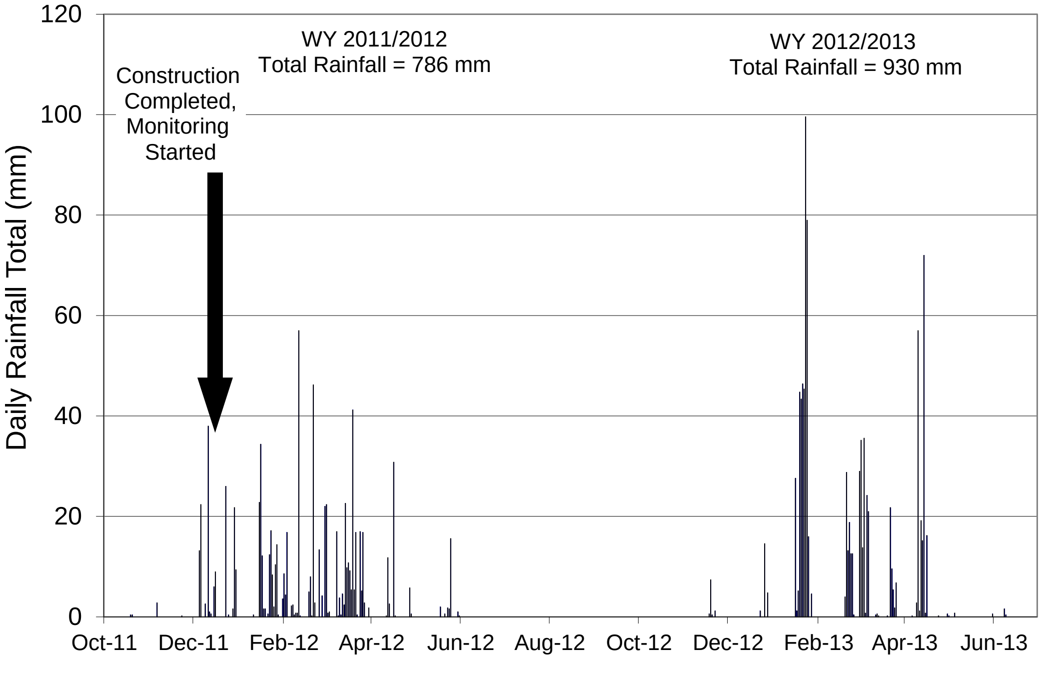
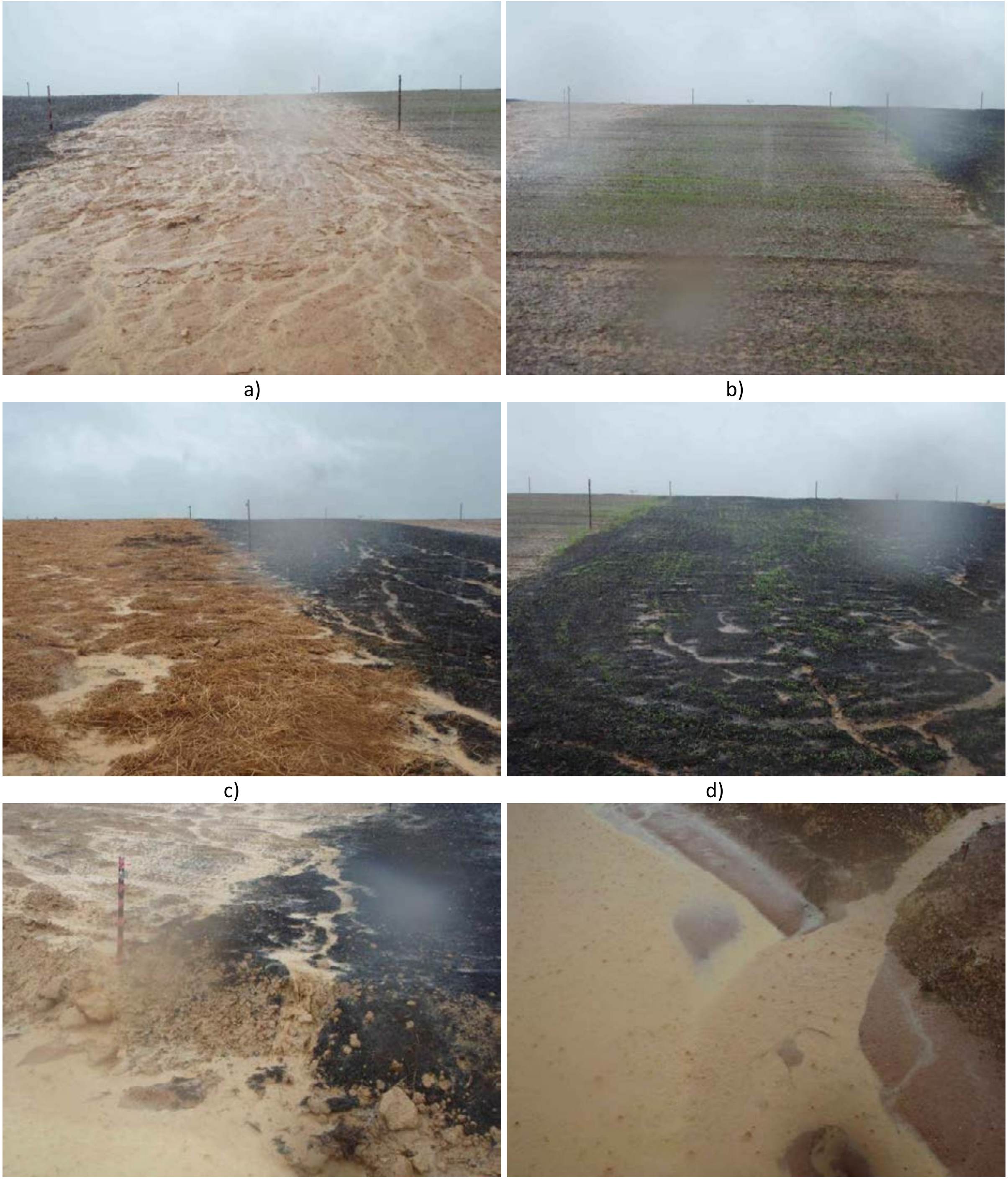


Figure 105 Daily rainfall totals during WY 2012 and WY 2013 at Crocodile Station

Qualitative Erosion Observations

At CRGC1-29 at the seven treatments plots (Figure 100; Figure 101), propagation of rill erosion from the bottom up started almost immediately during the first wet season rains, driven by overland flow from the top down (Figure 106). Rilling was most severe on bare plots without surface cover (Plots 1 & 5; Figure 106a; Figure 123). Rilling was least on the hydromulched surface (effectively a bonded fibre matrix, BFM), which protected the surface soils and reduced rilling during overland flow (Figure 106b; Figure 123). Sheet flow and rilling occurred on all plots regardless of treatment (Figure 106ad; Figure 123). Rilling appeared to be enhanced on plots that had a greater drop in relief at the creek confluence, which promoted the initiation of small headcuts (Figure 106e); however bare plots with less relief drop at the creek confluence still experienced much greater rill erosion (Figure 123). Soil erosion volumes and masses quantified with TLS surveys will be discussed below.



a) b)

c) d)

e) f)

Figure 106 Performance of trial plots at Gully 29 at CRGC1 during a rain events at a) plot 5 with gypsum only, b) plot 4 with hydromulch and gypsum, c) plots 6 & 7 with no gypsum and either straw or compost and exotic or native grass, d) plot 3 with gypsum, compost and exotic grass, e) headcutting and rilling initiating at the base of plot 6, and f) concentrated suspended sediment runoff from plot 1.

Vegetation Cover Variability

April 2012:
Average percent ground cover at two locations in each plot was estimated for live standing grass, live standing weeds, and dead organic ground cover (mulch) in April 2012 after the wet season. Before conditions in late-Dec 2011 were assumed to have zero percent grass cover and 100% dead organic ground cover at compost, hydromulch, and straw plots (Plots 2,3,4,6,7). During WY 2012, grass cover at all plots was partially influenced by cattle and wallaby grazing over the WY 2012 wet season. Cattle broke down the exclusion fence around the plot and had access to the sweet grass growth for several weeks in early March 2012 before the fence was repaired. Grazing was uniform by plot and mostly concentrated on shoots and young seed heads. Wallabies were also periodic grazers of the plots throughout the year, as documented in motion detection cameras.

In Apr-2012 at CRGC1-29, the highest grass cover occurred on plots sown with stoloniferous exotic grasses along with gypsum and mulch (plots 3 & 4; Figure 107; Figure 108). Plots with native grasses had sparser live cover due to plants growing in tuffs rather than spreading across the surface (Figure 108). Grass cover was reduced on soils without gypsum application (plots 6 & 7). Grass cover was extremely low on plot 7 seeded with exotic grass and covered with straw mulch with no gypsum. On un-seeded plots, volunteer grass and weeds species colonised small areas (plots 1 & 5) but was minimal overall. On all plots, most of the remaining area not covered by either live grass or dead mulch was composed of eroded rills and zones of sheet flow erosion (Figure 108).

Generally similar results were obtained at GCGC60/61, but there native grasses had slightly better cover than exotic grasses (Figure 107; Figure 109). The exotic grass and straw treatment (plot 9) performed better than CRGC1-29 (plot 7), but was not much better than volunteer recruitment of grasses into the bare gypsum-only plot from surrounding environments (plot 10).

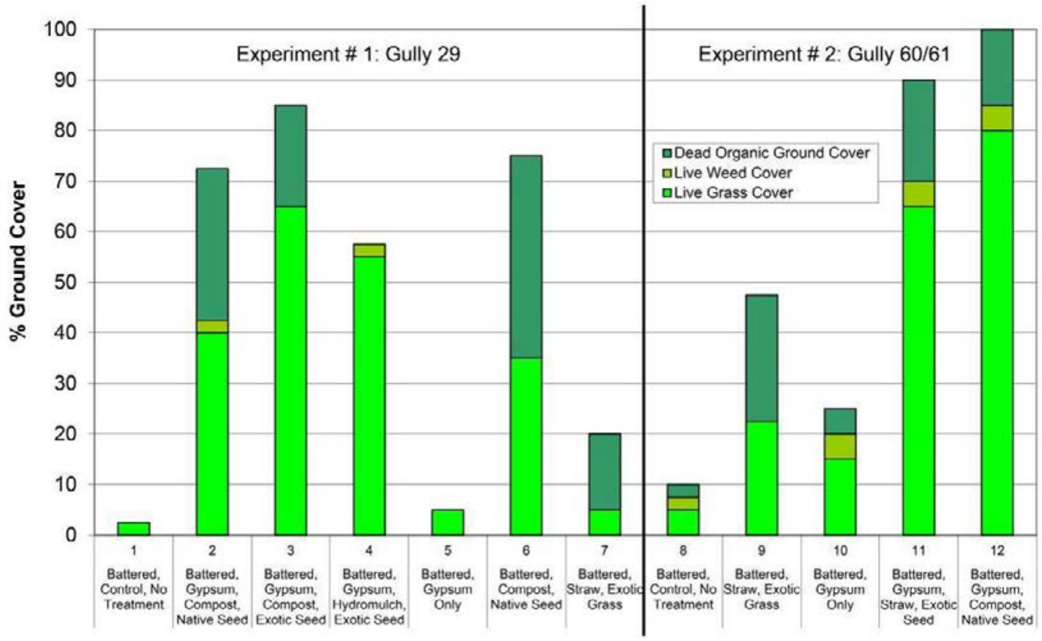


Figure 107 April 2012: Average percent (%) ground cover of live standing grass, weeds, and dead organic matter (mulch) at two locations per plot at CRGC1-29 and CRGC60/61 at the end of the wet season.

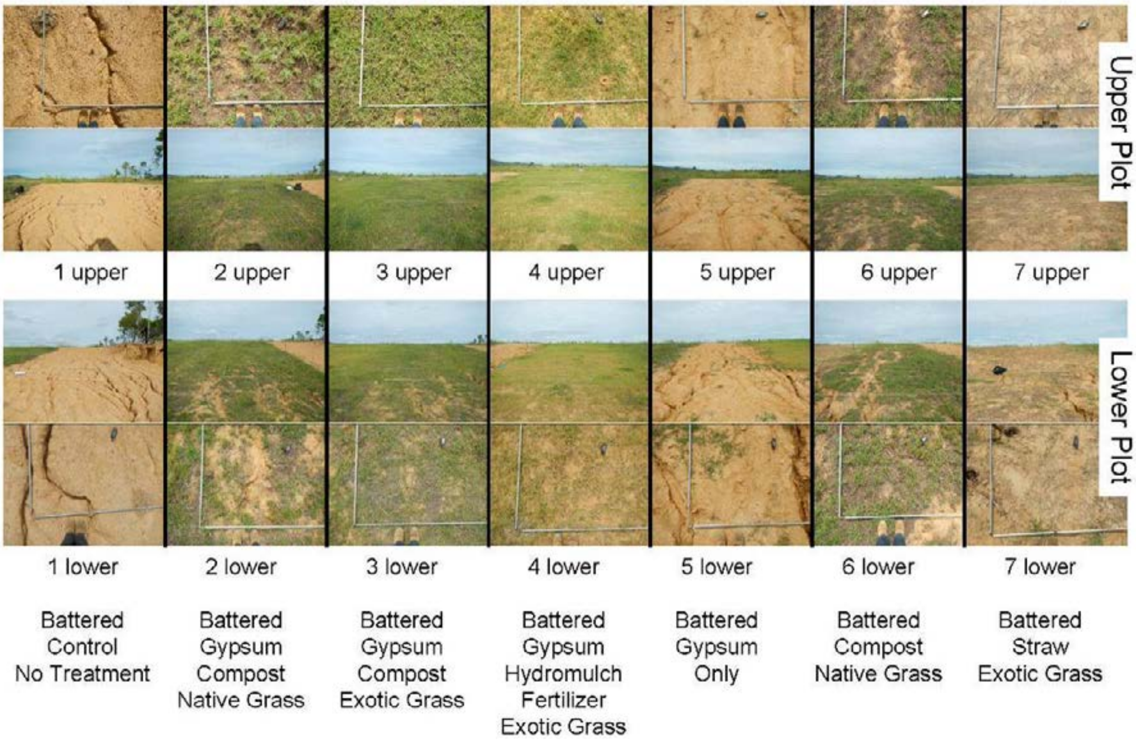


Figure 108 April 2012: CRGC1-29 plots and vertical and oblique photographs of upper (top) and lower (bottom) plots. Vegetation grid (4 m^2) is included for reference in the photographs.

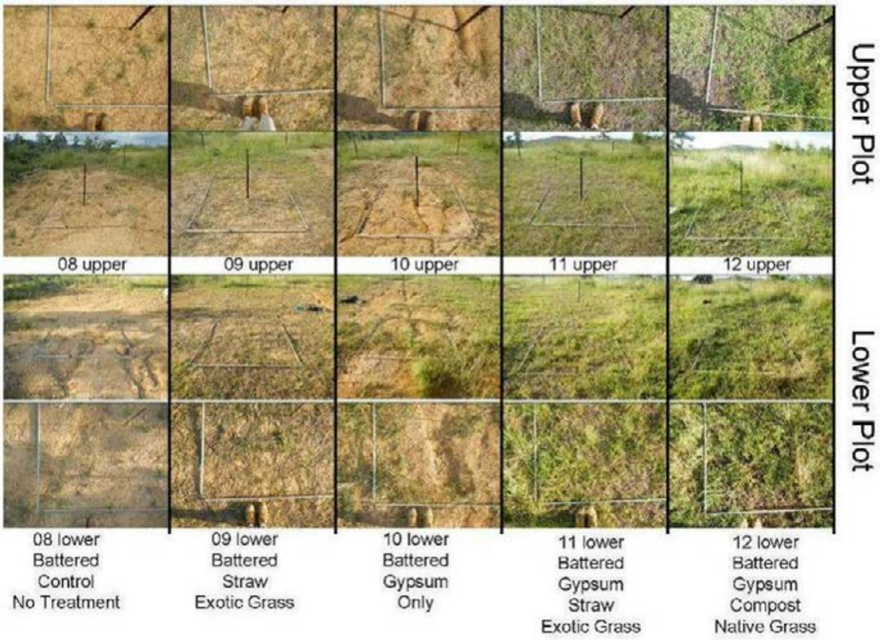


Figure 109 April 2012: CRGC60/61 plots and vertical and oblique photographs of upper (top) and lower (bottom) plots. Vegetation grid (4 m^2) is included for reference in the photographs.

November 2012:

Live and dead vegetative cover had reduced on average 5-10% over the dry season due to the desiccation of annual and perennial vegetation cover (Figure 110). Standing biomass was greatly reduced. Overall, the patterns of cover remained similar to April 2012, with plots treated with gypsum, mulch and grass having the greatest cover before wet season rains (Figure 111; Figure 112). Live vegetated cover was dominated by tussocks of perennial native grass and runners of stoloniferous exotic grass, while minimal live and dead weed cover was dominated by introduced pasture legumes and desiccated annual weed stalks.

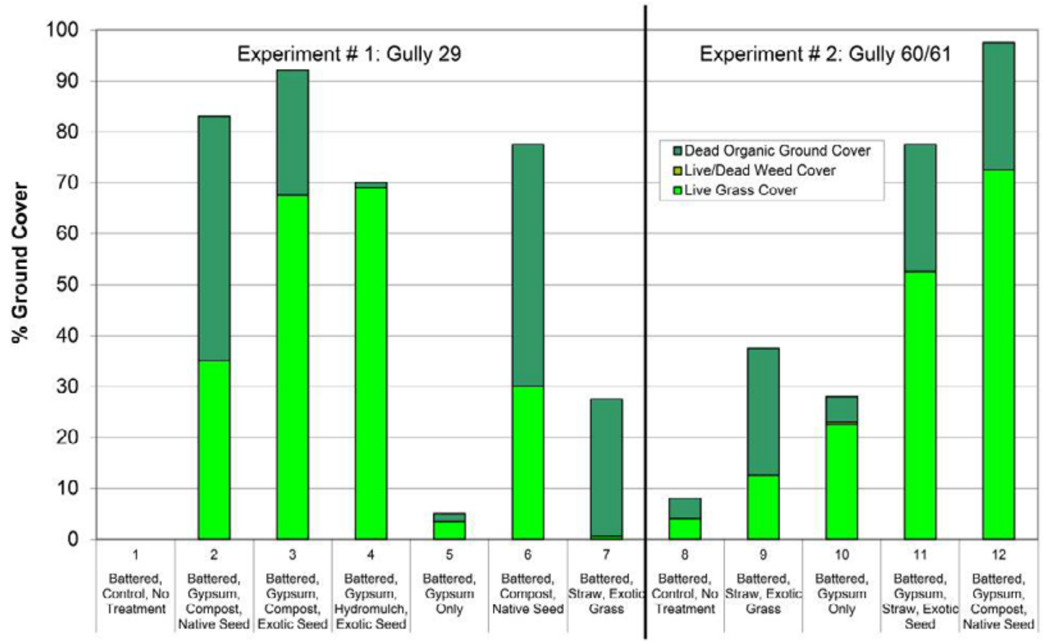


Figure 110 November 2012: Average percent (%) ground cover of live standing grass, weeds, and dead organic matter (mulch) at two locations per plot at CRGC1-29 and CRGC60/61 at the end of the wet season.

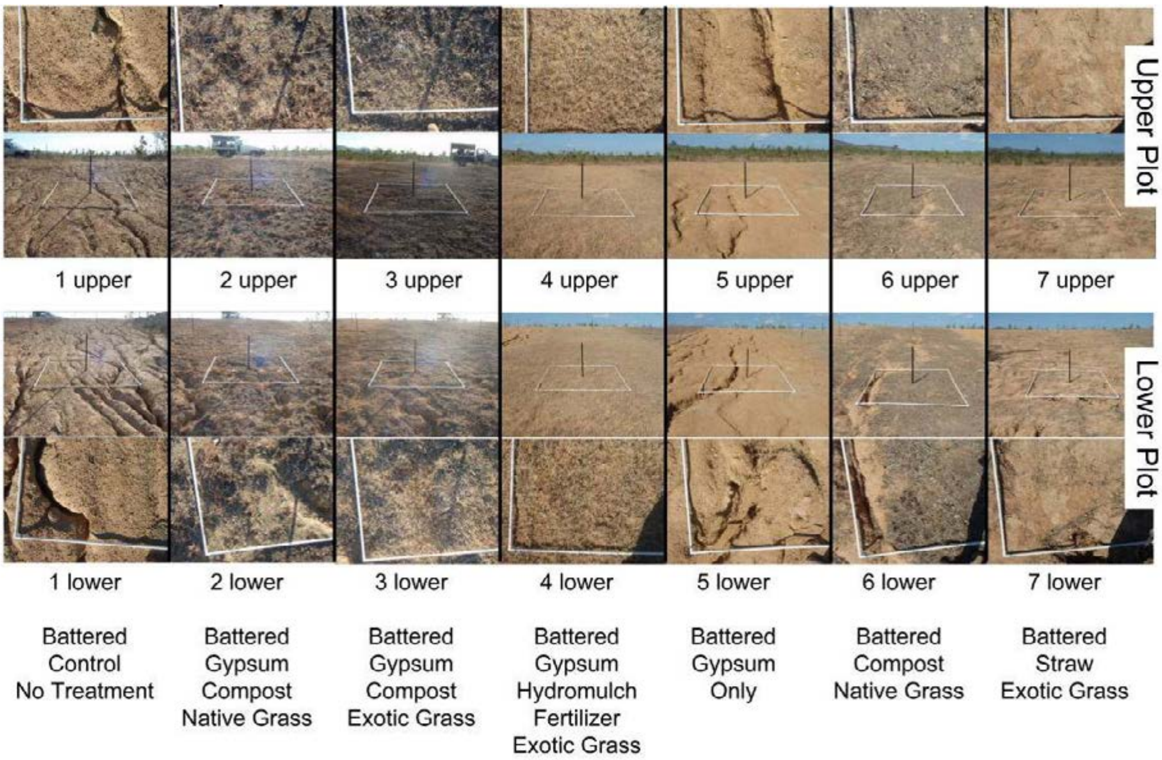


Figure 111 November 2012: CRGC1-29 plots and vertical and oblique photographs of upper (top) and lower (bottom) plots. Vegetation grid (4 m^2) is included for reference in the photographs.

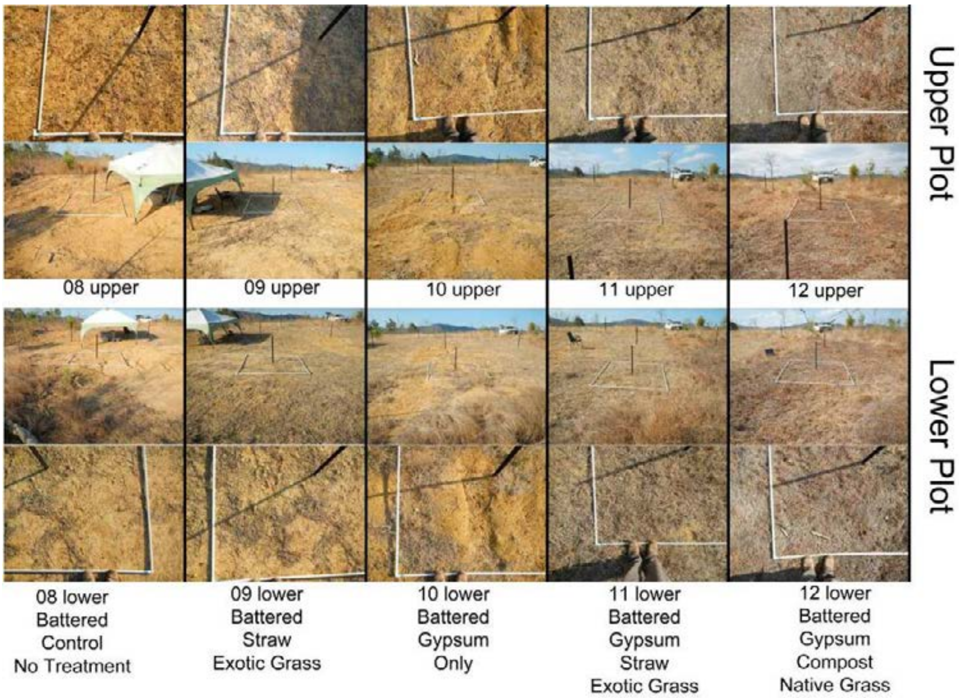


Figure 112 November 2012: CRGC60/61 plots and vertical and oblique photographs of upper (top) and lower (bottom) plots. Vegetation grid (4 m^2) is included for reference in the photographs.

April 2013:
Despite a slow start to the WY 2013 wet season with little vegetation growth until late January (Figure 105), vegetation growth responded well on the plots through February and March 2013. Cattle did not have access to the plot areas through WY 2013, despite some continued grazing by wallabies, which resulted in better cover outcomes and improved seed production. By April 2013, plots originally treated with native grass, compost, and gypsum had the best live vegetation cover (Figure 113; Figure 114; Figure 115), which is in partial contrast to April-2012 conditions (Figure 107). While plots originally seeded with exotic grass, mulch and gypsum continued to have decent cover, their biomass and seed production was lower and less vigorous than native plots with similar treatments (Figure 114; Figure 115). This could possibly be a result of stoloniferous exotic grasses putting more energy into root and runner production.

Abundant seed head production by April 2013 allowed for the identification of grass species by plot to detect changes in community composition after initial seeding in 2011. It became clearly evident that significant grass colonization and weed invasion had occurred into plots over the 16 month (2-wet season) assessment period. Plots 2, 6, and 12 originally seeded with native species (*Themeda triandra, Heteropogon contortus, Dichanthium sericeum*) had been invaded by exotic grasses (*Urochloa mosambicensis; Dactyloctenium aegyptium; Chloris inflate; Bothriochloa pertusa*), other native grasses (*Eriochloa pseudoacrotricha; Ectrosia nervilemma; Panicum seminudum*), in addition to several weeds species (*Hyptis suaveolens; Stylosanthes humilis; Sida trichopoda*) (Appendix 10.6). Both Black Spear and Queensland Blue grass (*Heteropogon contortus, Dichanthium sericeum*) continued to be present and locally dominant, but Kangaroo grass (*Themeda triandra*) became largely absent in plots except for a few individual plants. The success of Kangaroo grass could have been influenced by poor seed germination, grazing pressure by cattle and wallabies, competition by other grasses, and drought stress.

On plots 3, 4, 6, 9 and 11 originally seeded with exotic grasses (*Urochloa mosambicensis; Bothriochloa pertusa*), these exotic species remained present and often dominant. However, they were also invaded by a variety of other exotic grasses (*Dactyloctenium aegyptium; Chloris lobata; Chloris inflate; Themeda quadrivalvis*) and native grasses (*Eriochloa pseudoacrotricha; Ectrosia nervilemma; Panicum seminudum*), in addition to several weeds species (*Hyptis suaveolens; Stylosanthes humilis; Sida trichopoda*) (Appendix 10.6).

Grass colonization onto bare plots not originally seeded with grass was sporadically covered by exotic grasses (*Dactyloctenium aegyptium; Chloris lobata; Sporobolus coromandelianus; Urochloa mosambicensis; Bothriochloa pertusa*), with a few native grasses (*Ectrosia nervilemma*), and some weed species (*Hyptis suaveolens; Stylosanthes humilis*) (Appendix 10.6).

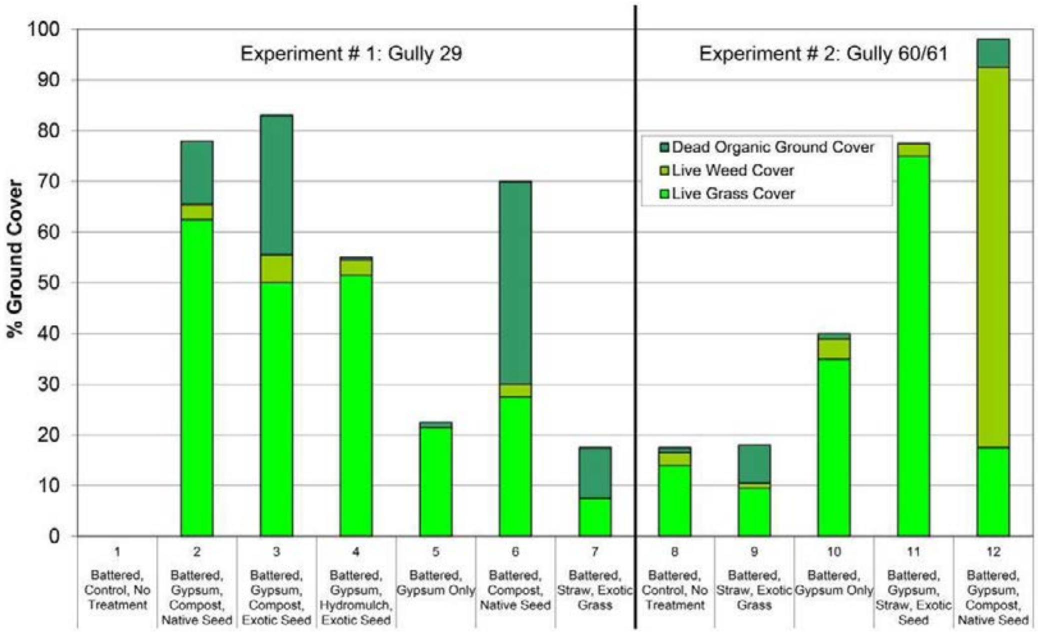


Figure 113 April 2013: Average percent (%) ground cover of live standing grass, live weeds, and dead organic matter (mulch) at two locations per plot at CRGC1-29 and CRGC60/61 at the end of the wet season.

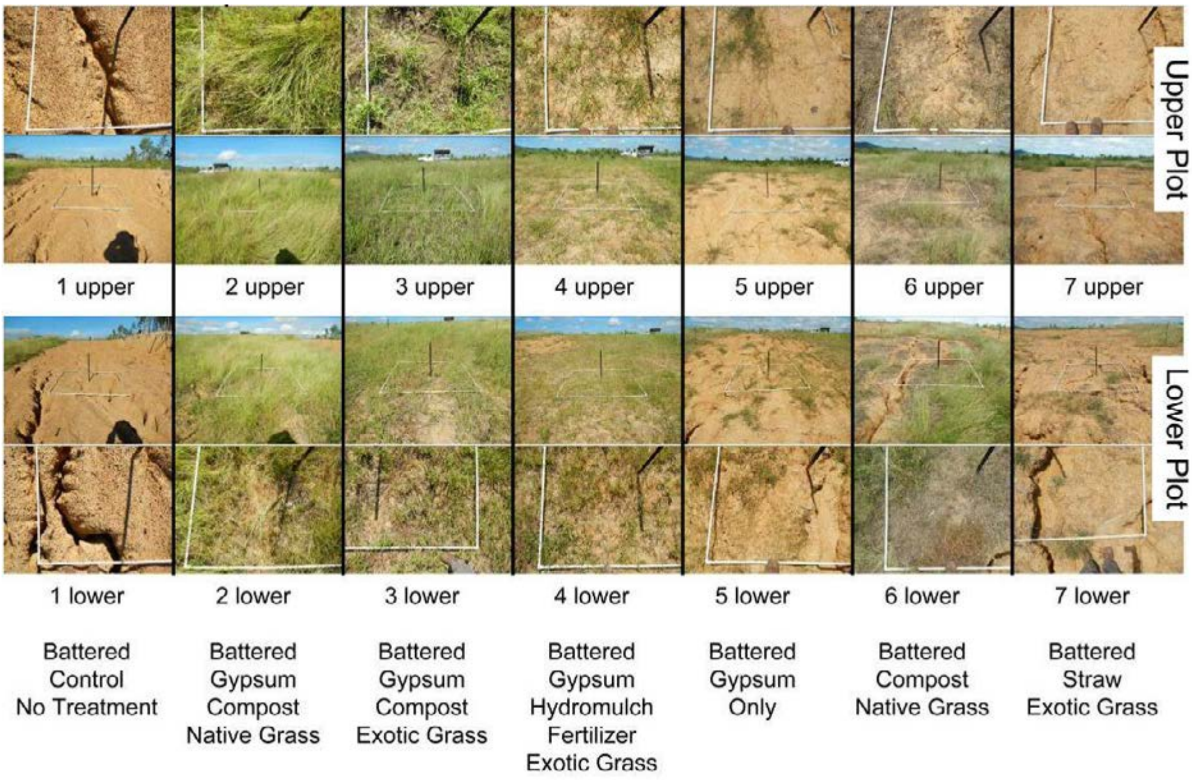


Figure 114 April 2013: CRGC1-29 plots and vertical and oblique photographs of upper (top) and lower (bottom) plots. Vegetation grid (4 m^2) is included for reference in the photographs.

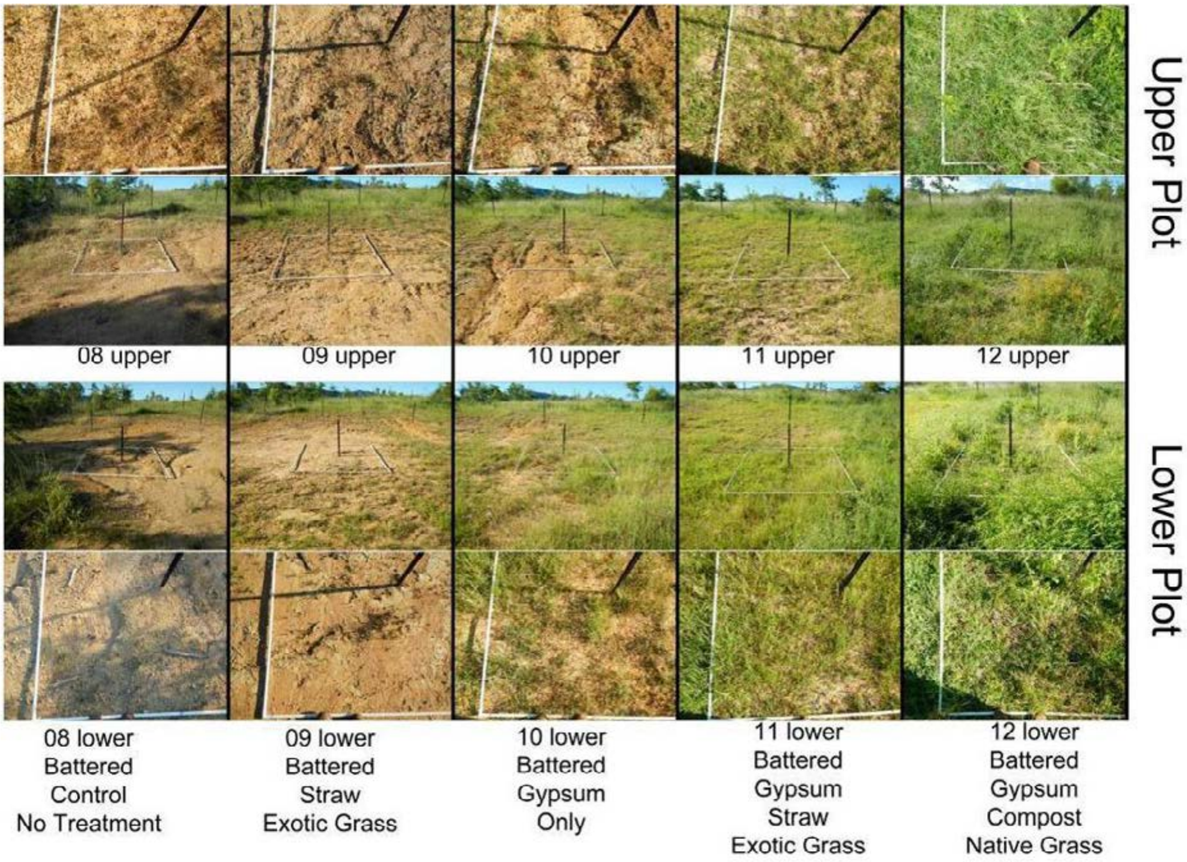


Figure 115 April 2013: CRGC60/61 plots and vertical and oblique photographs of upper (top) and lower (bottom) plots. Vegetation grid (4 m^2) is included for reference in the photographs.

<u>*Root Biomass*</u>

Grass root biomass, plant height, and above ground biomass displayed modest variability for the 16 native and exotic plant species measured with 75 mm wide by 14 cm deep tube cores at Plots 2 and 3 (Figure 116). The species with the lowest root biomass were the exotic wynn cassia (*Chamaecrista rotundifolia*) and Egyptian crowfoot grass (*Dactyloctenium aegyptium*) (Appendix 10.6). The species with the highest root biomass were native Queensland bluegrass (*Dichanthium sericeum*) and exotic Indian goosegrass (*Eleusine indica*) and Rhodes grass (*Chloris inflata*). However these species also had some of the highest above ground biomass, which was partially correlated to root biomass. Other native perennial species such as black spear grass (*Heteropogon contortus*) and kangaroo grass (*Themeda triandra*) had good root biomass and standing cover, as did the annual native *Panicum seminudum*. The common exotic Indian bluegrass (*Bothriochloa pertusa*) had modest root density, while the exotic, stoloniferous sabi grass (*Urochloa mosambicensis*) had a high root biomass but low plant height and above ground biomass.

From these data it appears that a range of grass species can be utilised for stabilizing sodic alluvial soils, with some species having greater above ground and root biomass than others. However the exact implications for erosion control remain unknown for many of these species, as data on maximum root depth, root strength and increased soil cohesion from roots is unknown (e.g., Simon et al. 2013). Comparisons of erosion volumes between perennial tufted grass and stoloniferous grass will be discussed below.

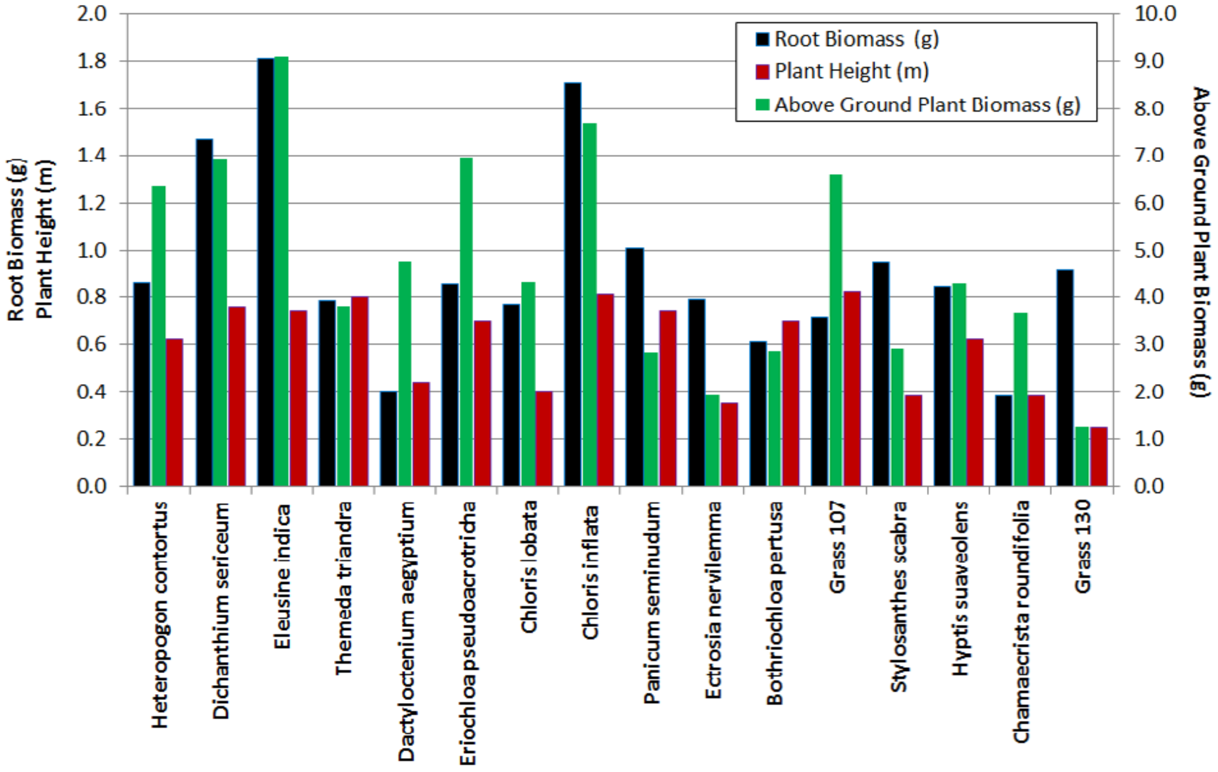


Figure 116 Differences in grass and herb root biomass, above ground biomass, and plant height for 16 species collected during April 2013 at CRGC1-29 Plots 2 and 3 (treated identically with gypsum and compost).

Soil Chemistry Changes

Application of ~ 80 t/ha equivalent of gypsum ($CaSO_4$) at treatment plots to ameliorate the sodic soils resulted in dramatic declines at the soil surface (<5cm) in exchangeable sodium percentage (ESP; Figure 117) and to a lesser extent exchangeable magnesium percentage (EMP; Figure 118). Sites treated with gypsum typically reduced in ESP values to below 5 % at the surface (<5cm) by the end of the wet season. Since soil chemical analysis targeted cations on clay particle exchange complexes by pre-treating soils with ethanol/glycerol and using ammonium chloride as an extractant to avoid dissolving solid phase gypsum (Rayment and Higginson 1992), the reduction in ESP was likely from actual calcium replacement of sodium on exchange sites, rather than dilution of the soil by volume. ESP values declined through the wet season (Figure 117), presumably due to the ongoing dissolution of solid phase gypsum and incorporation into the soil. The exception was the bare gypsum plot 5, where sheet erosion and deep rilling could have removed some of the applied gypsum. Furthermore, variability in ESP at the control sites on the soil surface indicated the potential for either incomplete initial soil mixing by bulldozer, creating local variability, or perhaps laboratory analysis error. A decline in ESP at sites treated with grass seed and mulch but not gypsum (plots 6 and 7 and 9) was also unexpected (Figure 117), and could be an artefact of adding organic matter to the soil, measurement error, and/or soil mixing variability.

Soil surface (<5cm) reductions in exchangeable magnesium percentage (EMP; Figure 118) were also observed at all gypsum treatments, but EMP values only reduced to about 10%. Unlike ESP, declines in EMP were not observed at sites treated with just grass and mulch but not gypsum, with the exception of plot 9. Overall, both exchangeable sodium and magnesium declined in surface soils (<5cm) and were replaced by exchangeable calcium.

The reduction in ESP values at the immediate soil surface (<5cm) after gypsum application did not continue with depth (Figure 119). At 10cm depth in Oct-2012, the ESP values were >5 ESP. At 40-50cm depth, ESP values reached 50%, similar to values for deep soils before regrading (Figure 119). These data suggest that the penetration of surface gypsum application was minimal after one below-average wet season and dominance of surface runoff. The use of fine 5 µm gypsum (Gypflo) on plot 4 in addition to bulk -2 mm gypsum did not have a major effect on ESP values at depth compared to bulk -2 mm gypsum on plot 2 (Figure 119). Gypsum application to the soil surface thus would only have localised effects on soil physical and chemical properties at the surface, and not depth. The physical process of regrading the gully and mixing gully surface and sub-soils onto the new battered surface did not substantially dilute original ESP values, but rather just created average ESP conditions for the bulk of the gully soil profile dominated by ESP values between 40-60%.

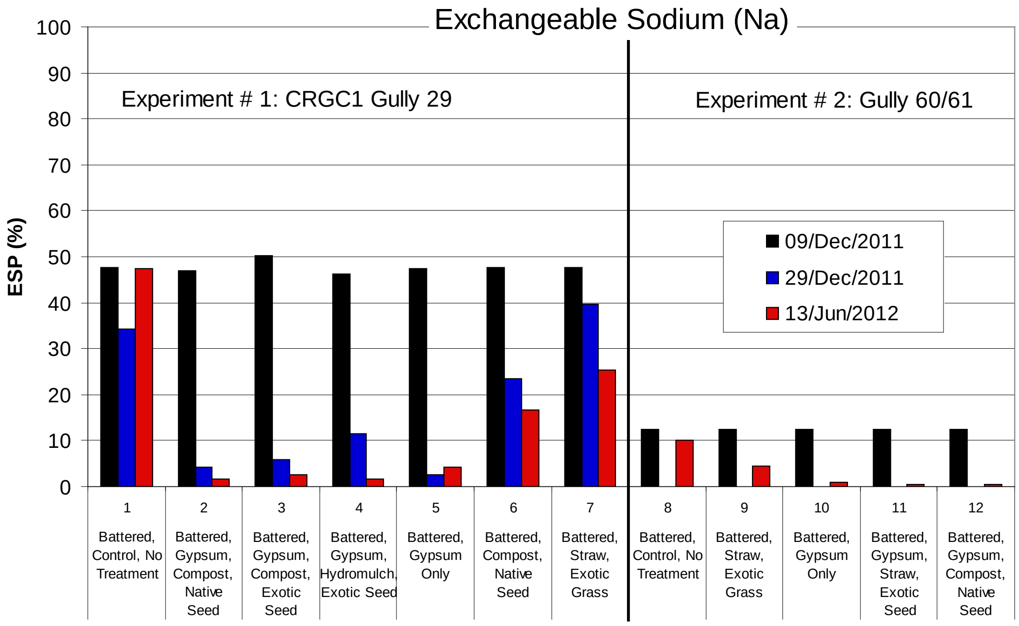


Figure 117 Exchangeable sodium percentage (ESP) at CRGC1-29 and CRGC60/61 before, during, and after gypsum application (~80t/ha -2mm gypsum) in WY 2012.

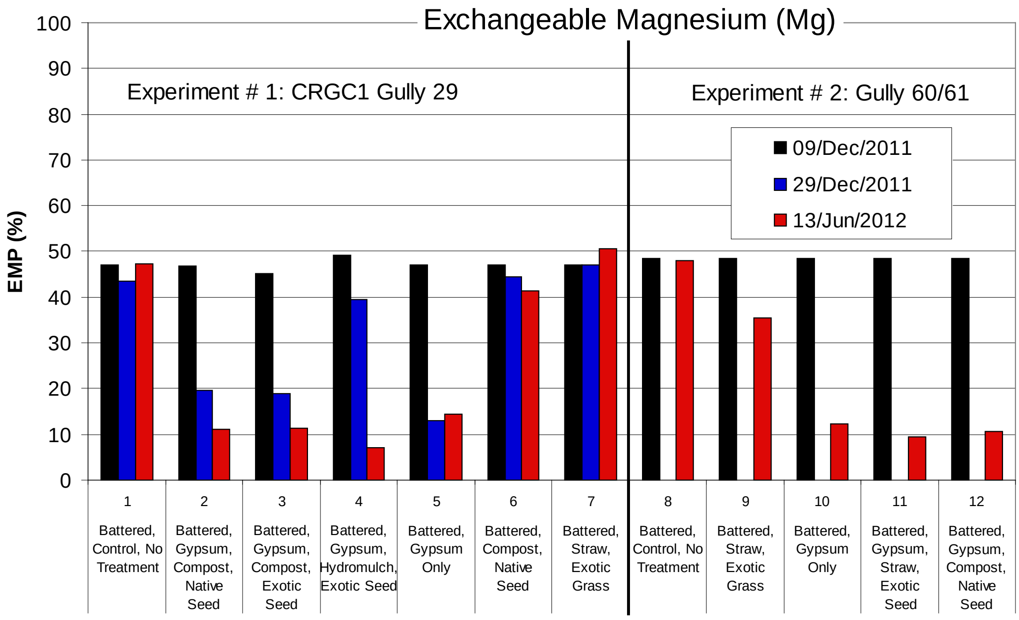


Figure 118 Exchangeable magnesium percentage (EMP) at CRGC1-29 and CRGC60/61 before, during, and after gypsum application (~80t/ha -2mm gypsum) in WY 2012.

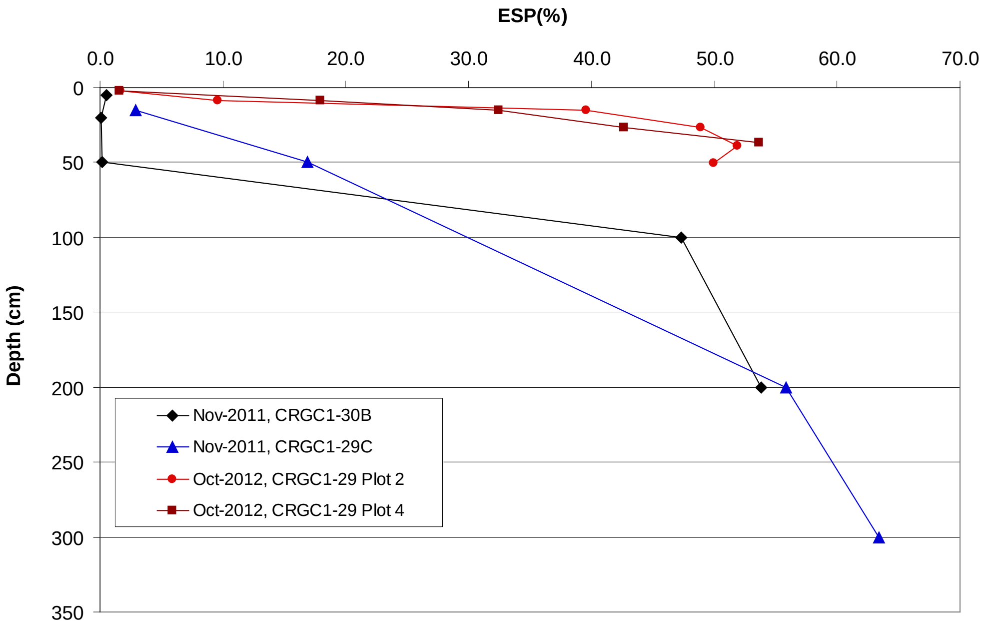


Figure 119 Changes in ESP with depth before (Nov-2011) and after (Oct-2012) gully regrading and the addition of gypsum to the regraded gully surface.

Bulk Density and Particle Size Distributions

Bulk density measurements at un-disturbed in situ gully profiles generally increased down profile from 1.6 g/cm^3 at well vegetated pasture surfaces to 1.85 g/cm^3 at sodic clay sub-soils exposed at the gully base (Figure 120). However, bulk density was reduced at 200cm , perhaps due to coarse soil texture at an alluvial soil horizon. Furthermore, surface bulk density was reduced in scalded zones around the gully perimeter, where soil organic matter and vegetation had been stripped off during the initial phases of gully erosion and increased bulk densities > 1.85 g/cm^3.

At bulldozed and battered soil plots at CRGC1-29 and CRGC60/61, resultant bulk densities were measured in October 2012 after one wet season and following initial treatment of some plots with gypsum and vegetation and organic matter. Soil bulk densities ranged from 1.68 g/cm^3 to 1.83 g/cm^3, and averaged 1.76 g/cm^3 (Figure 121), which excluded any surface organic material on the soil. The down profile average for undisturbed gully soils was also 1.76 g/cm^3 (Figure 120). Variability in bulk density did not follow patterns of chemical and biological treatment of soils at experimental plots (e.g., the BD of gypsum and mulch covered plots were as high as bare plots or higher). These results likely reflect variability in mixing and settling after plot battering, possible errors in field and laboratory analysis, and other unknown factors.

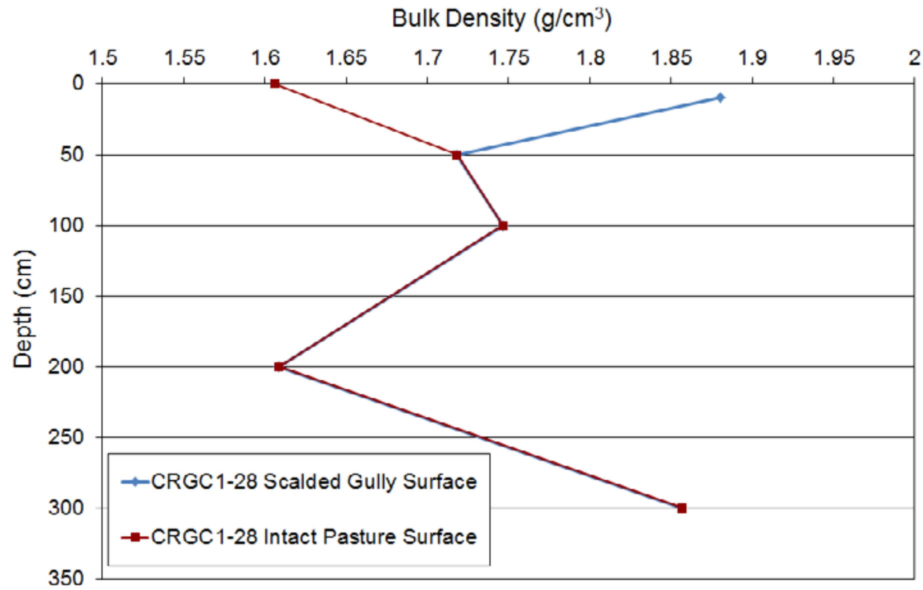


Figure 120 Changes in bulk density (g/cm^3) with depth at a CRGC1-28 intact gully profile. Note the difference between intact and scalded surface soils.

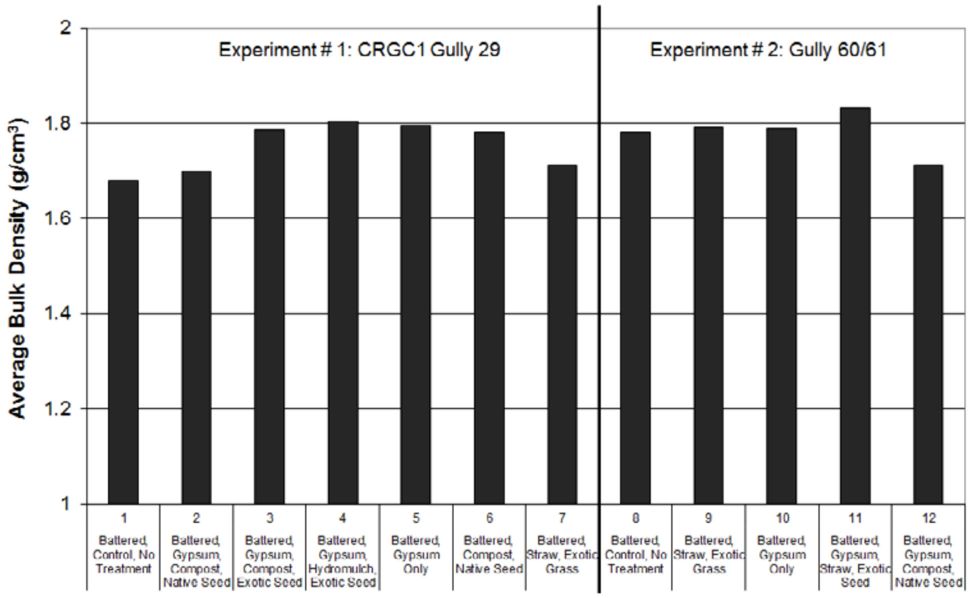


Figure 121 Differences in average bulk density (g/cm^3) at experimental control and treatment plots measured in October 2012 after one wet season and initial treatment.

The particle size distributions of soils before and after treatment are still pending from laboratory results and are unavailable for this report.

Infiltration Rates

Infiltration measurements using a double ring infiltrometer (ASTM 2009) displayed distinct differences between plots (Figure 122), often in contrast to patterns of bulk density above (Figure 121). At CRGC1-29 (experiment #1), the control plot 1 and plot 7 not treated with gypsum and with little vegetation cover had the lowest infiltration rates (<5 mm/day). Adding gypsum increased the infiltration rate into bare soils (plot 5). Adding just compost cover and native grass also increased the infiltration rate (plot 6). The poor establishment of exotic grass on plot 7 and decomposition of straw resulted in poor surface cover (Figure 107; Figure 108), which could have influenced the lower infiltration rates. The influence of combined treatments of gypsum, compost and mulch, and grass cover were additive or possibly synergistic. The highest infiltration rates were measured at plots with good exotic grass cover, gypsum and compost or mulch (up to 20 mm/day; Figure 122).

At CRGC1-29 (experiment #1), despite increases in infiltration rates with multiple treatments, treatment effects were still not great enough to increase infiltration rates to the point where soils could accommodate typical event or daily rainfall totals. Daily rainfall totals up to 60 to 100 mm/day would exceed the average infiltration capacities of up to 20 mm/day (Figure 105). The resultant runoff of water not infiltrated was critical in generating rill erosion on all plots (Figure 123). Thus, soil amendments of gypsum, compost/mulch and grass cover only partially mitigated runoff generation from direct rainfall, but they did likely increase the threshold at which runoff was generated. The treatments also likely influenced the resistance of the soil to erosion from both direct raindrop impacts and overland flow shear stress, via cover protection, roughness, and grass root binding of soil. However, managing excess surface water runoff will still be needed under ideal grass cover and soil conditions.

In contrast at CRGC60/61 (experiment #2), adding gypsum, mulch and exotic or native grass increased infiltration rates from below 20 mm/day at the control plot to 100 mm/day or more at plots with gypsum or multiple treatments. The extremely low ESP and EMP values at plots treated with gypsum at CRGC60/61 (Figure 117; Figure 118) suggest that fully replacing sodium and magnesium with calcium on clay particle exchange sites can have major effects on soil structure and infiltration rates. However, other soil physical and chemical factors also could be influencing these differences in infiltration rates, such as variability in bulk density at the surface and depth (Figure 121). Regardless of cause, the resultant infiltration rates up to 100 mm/day match the typical daily rainfall intensities of 60-100 mm/day (Figure 105). The net result was very little surface and rill erosion at plots treated with gypsum, especially where good grass cover was also established (Figure 109; Figure 115).

As a comparison to these infiltration rates at gullied sub-soils high in ESP and clay content, measurements of infiltration were also conducted into non-sodic surface soils (predominantly sandy silt) in the adjacent well vegetated pasture and non-sodic surface soils that had become scalded due to loss of organic top soils and vegetation. In the non-sodic surface soils in the pasture (<0.5m deep; Figure 103), infiltration rates were 375mm/day, which would greatly exceed any extreme rainfall events. Scalded non-sodic surface soils had infiltration rates of 91 mm/day, still extremely high compared to sodic clay sub-soils. These data for this pasture indicate that surface water runoff would be rare under unsaturated conditions; with runoff occurring only after the top 0.5m of non-sodic soils had become saturated from multiple rainfall events during the wet season. These differences highlight the need to protect surface soils from erosion to maintain hydrological functions. Once these surface soils are stripped due to land use disturbance and intense weather events, exposing sodic clay sub-soils, hydrologic functions will diminish and accelerate deep gully erosion into generally impermeable sub-soils.

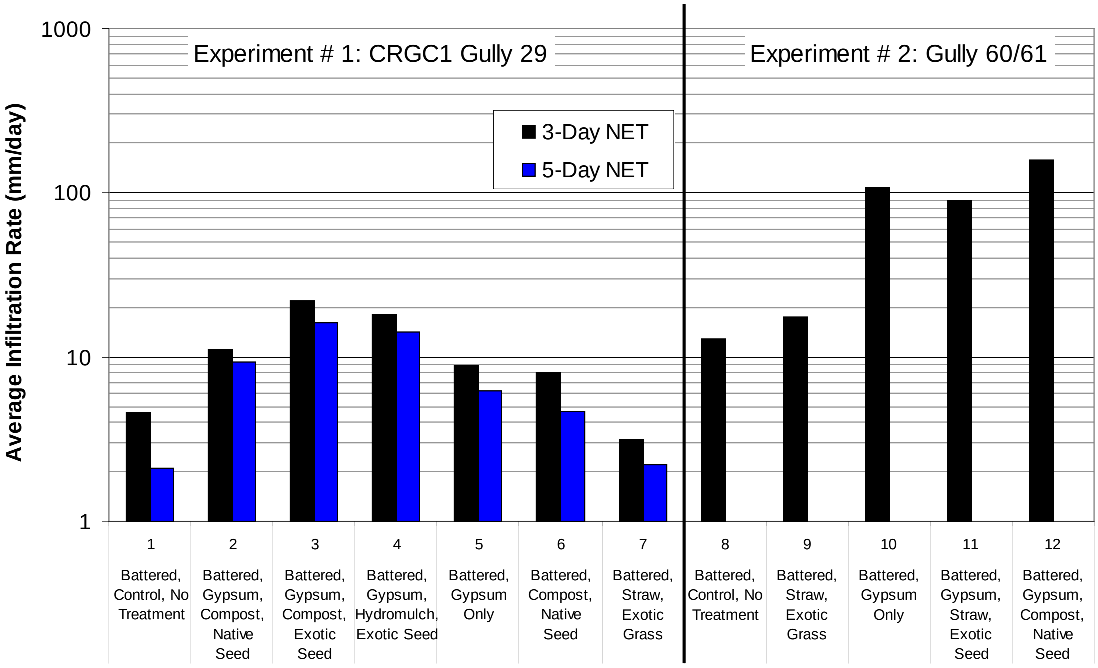


Figure 122 Average infiltration rates (mm/day) over 3 and 5 day trend periods measured at experimental plots using a double ring infiltrometer and corrected by local evaporation measurements.

Quantification of Soil Erosion Volume

At CRGC1-29 treatment plots and CRGC1-28 and CRGC1-32 control surfaces, soil erosion volumes over two wet seasons were calculated from TLS surveys in Dec-2011, Nov-2012 and May-2013. Erosion change data (erosion and deposition) over the WY 2012 and WY 2013 wet seasons are displayed below for CRGC1-29 (Figure 123; Figure 124). At CRGC60/61, surveys were only conducted in Dec-2011 and Nov-2012. At each original 7m x 25m plot at CRGC1-29, a smaller index area of 6m x 20m was used for erosion calculations to minimise border effects between plots. At each original 5m x 12m plot at CRGC60/61, a smaller index area of 2.5m x 6.4m was used. At CRGC1-28 and CRGC1-32 control surfaces, several different slopes and scarps and fluted surfaces with consistently high resolution point coverage were used to generate index areas for comparison. These slopes, scarps and fluted surfaces were analysed separately for internal and external comparison. At all sites, net erosion rates (erosion - deposition) were normalised to unit areas to obtain kg/m^2/yr. These net erosion data also can be compared to other plot metrics such as vegetation cover, ESP, infiltration rate, bulk density, and particle size.

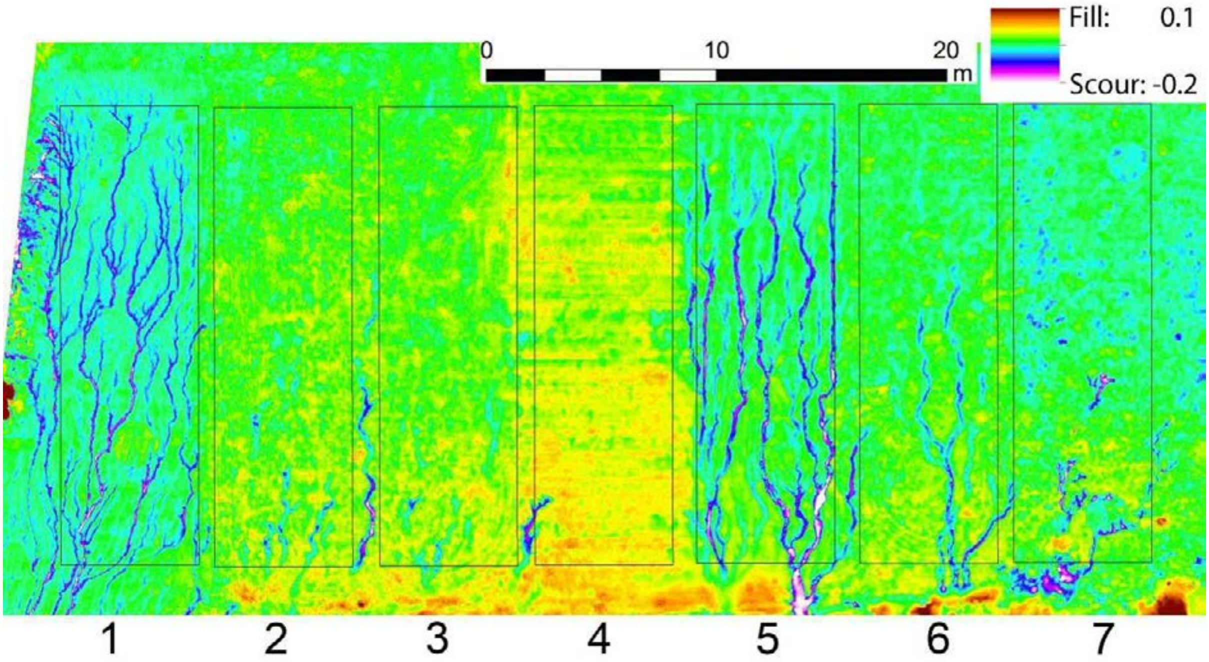


Figure 123 WY 2012 wet season (December 2011 to November 2012) terrestrial laser scanning (TLS) difference data at CRGC1-29 (Plots 1-7) showing erosion (scour: yellow-green-blue) and deposition (fill: brown). Erosion index areas (6m x 20m) of each plot are outlined in black. Note that some of the apparent deposition (brown) is actually grass growth that has been filtered out for calculations.

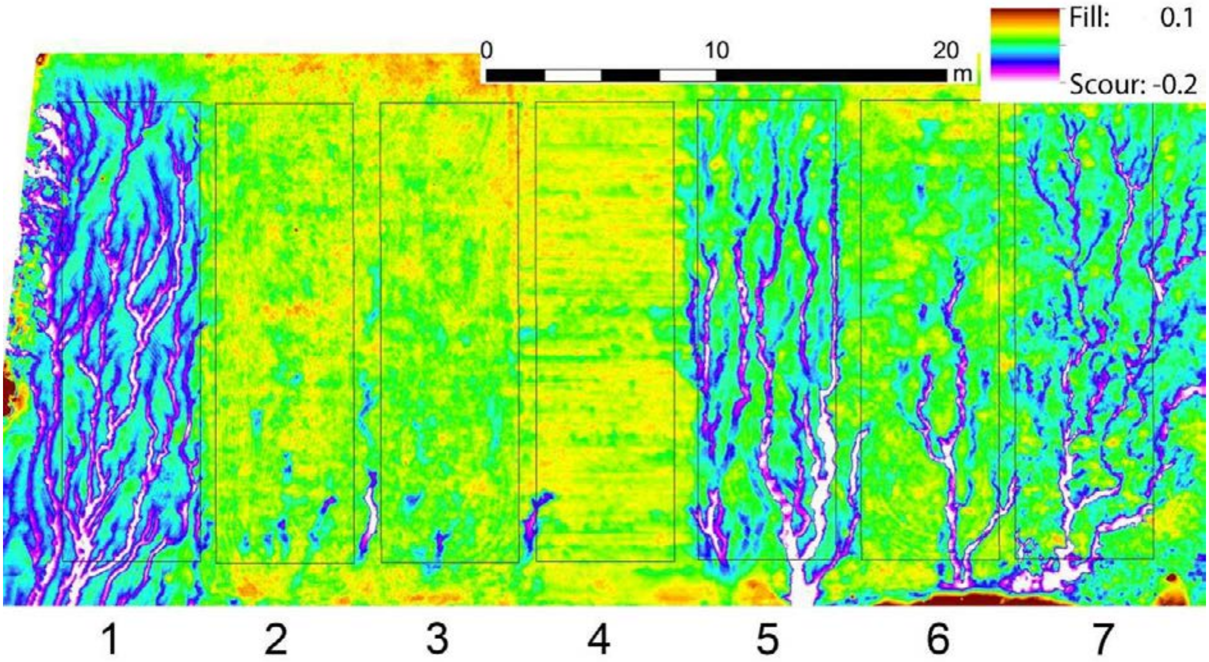


Figure 124 WY 2012 and WY 2013 wet season (December 2011 to May 2013) terrestrial laser scanning (TLS) difference data at CRGC1-29 (Plots 1-7) erosion (scour: yellow-green-blue) and deposition (fill: brown). Erosion index areas (6m x 20m) of each plot are outlined in black. Note that some of the apparent deposition (brown) is actually grass growth that has been filtered out for calculations.

At CRGC1-29, qualitative measurements using TLS surveys (Figure 123; Figure 124; Figure 125) confirmed qualitative observations (Figure 106; Figure 108; Figure 109) that rill density and depth were greatest on bare plots with no surface or vegetation cover (Plots 1 and 5). During the first wet season (2011-2012), the battered control plot (1) had net unit erosion rates (>100 kg/m^2/yr) that were 1.5 to 5 times higher than undisturbed slopes and gully scarps (<60 kg/m^2/yr) at adjacent control gullies (Figure 125). Adding gypsum to bare soils only slightly reduced erosion rates (Plot 5). These data indicate that disturbing gully scarps (i.e. battering) with heavy machinery without erosion control can actually increase erosion rather than decrease it. However, after the second wet season and deep rill and gully erosion at Plot 1, erosion rates had reduced toward background rates at undisturbed gully scarps and surfaces (Figure 125). The rapid formation of ferricrete nodules on bare gully surfaces helped protect the soil surface from raindrop impact over time from surface lags of nodules.

Plots covered with either straw or compost and sown with exotic or native grass (Plot 6 and 7) experienced reduced erosion rates compared to bare plots, but were still elevated above undisturbed control gullies (Figure 125). However, erosion rates had reduced toward background rates after the second wet season. Plots treated with both chemical and biological measures experienced the least amount of erosion. Plots 2 and 3 treated with gypsum, compost, and native or exotic grass experienced erosion rates similar to background rates during the first wet season, and below back ground rates by the second wet season as perennial grass vegetation played an increasing role in stabilizing slopes (Figure 125).

The use of a hydromulch mix with gypsum (Plot 4) experienced the lowest erosion rates of any plot during the first year, lower than background rates (Figure 125). The bonded fibre matrix (BFM) of the hydromulch protected the soil surface during the initial rains in December 2011, which reduced rilling during overland flow (Figure 106b; Figure 123). This initial resistance to erosion at the hydromulch plot provided historic contingency that altered antecedent conditions and minimised future erosion of rills into this plot (Figure 124). The opposite was true at other plots, where initial micro-rilling on covered but unvegetated surfaces set up and enhanced the potential for further deep rilling. In contrast, erosion at the hydromulch plot was dominated by sheet flow that stripped fine layers of soil and mulch from upper slopes and deposited them on lower slopes (Figure 123). The stoloniferous grasses used in the hydromulch (*Urochloa mosambicensis; Bothriochloa pertusa*) would have also contributed to sheet flow rather than rilling around perennial tussocks.

By the second wet season (WY2013), erosion rates on battered plots were below back ground rates at un-battered control surfaces (Figure 125), which was a combined result of declining erosion rates after initial soil disturbance, lags of ferricrete nodule formation on bare gully plots protecting the soil, and the increasing influence of perennial grass vegetation stabilizing slopes without cattle grazing. This was especially true on plots with compost and gypsum, which provided the best conditions for long-term perennial grass growth and invasion by additional grass species (Figure 113; Figure 114). Perennial grass growth on the hydromulch plot (4) struggled by the second year, both in terms of cover and biomass, possibly due to the lack of good organic mulch afforded to neighbouring plots. Erosion rates appeared to increase slightly at the hydromulch plot after the second year (Figure 125); but this condition was due to the difficulty in accurately measuring sediment deposition vs. grass growth in May 2013. Future surveys in November 2013 could improve measurements.

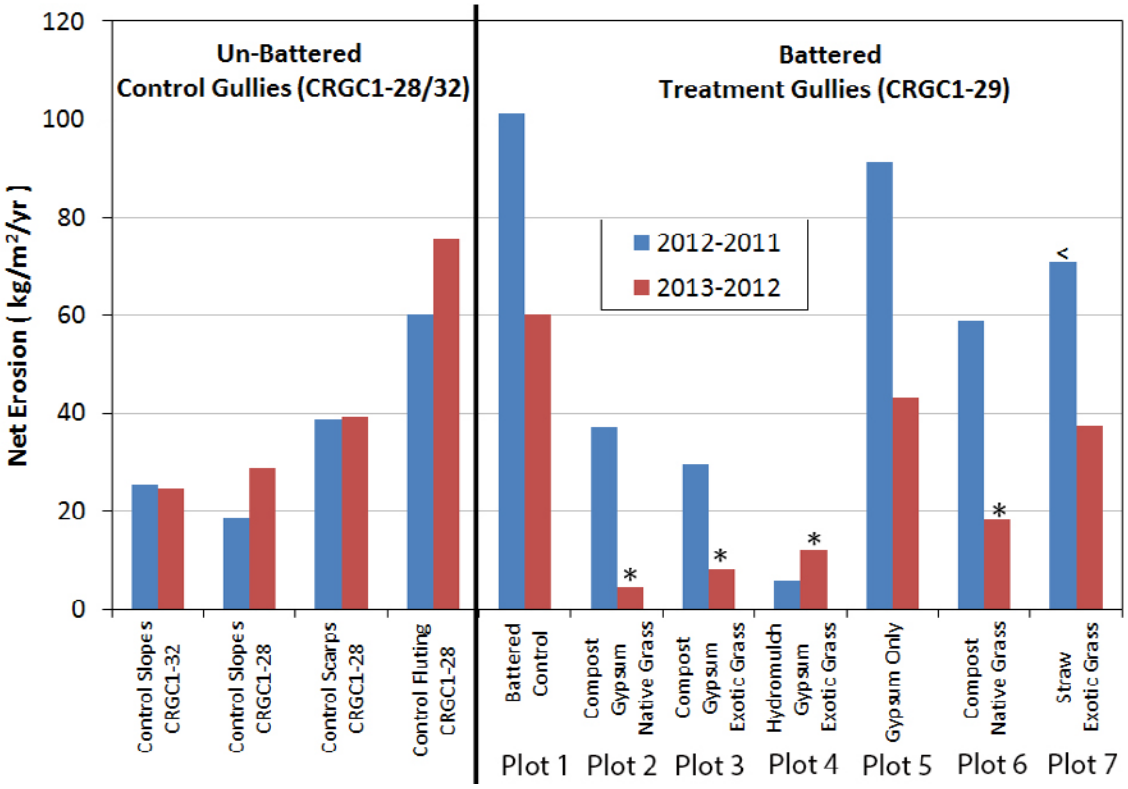


Figure 125 Net erosion (erosion + deposition) at CRGC1 control and treatment plots based on repeat TLS surveys. Note that net erosion values noted by < at plot 7 (2012-2011) were partially influenced by the inability to penetrate the dense straw at this site in Dec-2011 with TLS; thus, this value is a maximum. Note that net erosion values noted by * indicate that only gross erosion could be calculated, since mowed vegetation stubble in May 2013 surveys influenced apparent deposition and estimation of true net change. November 2013 surveys could reduce this uncertainty.

At CRGC60/61, TLS surveys conducted in Dec-2011 and Nov-2012 demonstrated that erosion was the greatest on the battered but untreated control plot (Figure 126). It was least on the plot treated with gypsum, compost and native seed (Figure 126), where vegetation cover was the greatest (Figure 109; Figure 112; Figure 115). All erosion rates at CRGC60/61 were at or below rates measured at undisturbed control plots (CRGC1-28/32; Figure 125). Measurements of accurate soil erosion rates were difficult at plots 9 and 11 treated with straw mulch due to the inability to survey through the dense straw in Dec-2011. Thus, these erosion rates are a maximum (Figure 126).

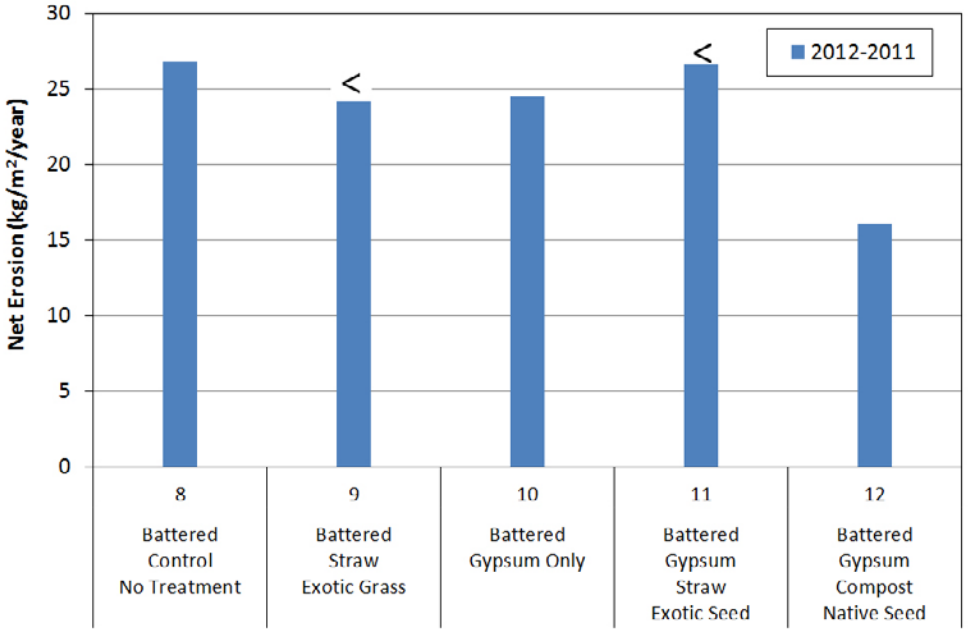


Figure 126 Net erosion (erosion + deposition) at battered CRGC60/61 control and treatment plots based on repeat TLS surveys. Note that net erosion values indicated by < at plots 9 and 11 were partially influenced by the inability to penetrate the dense straw at these sites in Dec-2011 with TLS; thus, these values are a maximum.

From repeat airborne LiDAR measurement in 2009 and 2011 ($1m^2$ pixels), it was estimated that 11.2 tonnes/year of sediment eroded from the gully lobe of CRGC1-29 ($13.0\ m^3$ over two years, soil bulk density of $1.73\ tonnes/m^3$). No estimate of deposition was available but it is assumed to be minimal at the gully scarp. Most of the measured erosion was concentrated at headcuts (Figure 99), but these data are likely a minimum since more subtle changes below the detection limit of airborne LiDAR were not measured. In comparison using TLS surveys at CRGC1-29, a net 47.4 tonnes/year eroded in WY 2012 wet season, while a net 22.04 tonnes/year eroded in WY 2013. While these data were collected by two different techniques at different scales and under different annual rainfall conditions, they do suggest that erosion possibly increased as a result of the full suite of treatments, at least during the first year on this site with many bare and partially treated plots. If hydromulch and gypsum had been applied to all the plots of CRGC1-29, then extrapolated erosion rates would have been 5 to 10 tonnes/year, lower than pre-treatment estimates from airborne LiDAR.

7.13.5.4 Discussion

The results from these experimental trials at the plot scale highlight several key issues regarding rehabilitation of alluvial gullies.

First, without appropriate consideration of rehabilitation measures and level of effort, physical intervention can actually increase erosion and sediment supply in the short-term. This is all too common when machine operators regrade gullies along roads and fences in the Normanby catchment (e.g., Figure 75; Figure 87; Figure 93; Figure 128; Figure 136; Figure 140; Figure 143; Figure 144; Figure 147). Rehabilitating battered gully slopes with sodic soils requires the addition of chemical and biological (vegetation, mulch) amendments, or alternatively importing non-sodic top soil or rock to bury the sodic soils.

Second, these experiments demonstrate the importance of both live perennial grass cover and dead organic mulch or compost in protecting the soil surface from raindrop impact, anchoring the soil with roots, and providing a good organic growing medium for long-term grass growth (compost). The patterns of decreasing erosion with increasing grass and mulch cover in these gully rehabilitation experiments support earlier experiments in Australian rangelands on the importance of cover to minimise water and sediment yield (McIvor et al. 1995; Scanlan et al. 1996; Silburn et al. 2011). Both tufted perennial grasses and stoloniferous perennial grasses were effective at erosion control. Stoloniferous perennial grasses provided more uniform ground cover and resisted early tendencies for rill erosion. Tufted perennial grasses were more prone to rilling around tufts, but produced greater above ground biomass, vegetation litter and cover that protected the soil surface from intense rainfall over the long-term. More research is needed on the rooting depths and soil cohesion properties of both native perennial tuft grasses and exotic stoloniferous grasses, especially in sodic soils.

For erosion reduction in rehabilitated gully slopes, soil cover and protection during the initial rains after construction are critical to avoid micro-rilling and positive feedback loops that create deep rills and gullies. Hydromulch provided this short-term soil protection as a bonded fibre matrix that reduced undermining of the mulch cover and rill formation. However, compost provided a better long-term growing medium and nutrients for grass growth. The future combined use of hydromulch and compost could be trialled, such as applying hydromulch over a layer of compost, or perhaps adding compost to the soil surface one year after initial hydromulch application. Tests would be needed to determine effectiveness and optimal grass growth (i.e., undermining, grass smothering). Alternatively, more formalised methods using compost blanket mixtures (Faucette et al. 2005; 2007; 2009a) could also be tested on sodic soils of alluvial gully slopes.

Third, the use of gypsum ($CaSO_4$) at high application rates (~80t/ha) to amend sodic soils with high exchangeable sodium percentage (ESP) was effective at reducing soil surface ESP values from 50 to 5%. This change in soil chemistry enhanced grass vegetation establishment and colonisation success and increased soil infiltration rates at the soil surface. However, gypsum addition to the soil surface did not immediately affect sub-soil ESP values beyond 20 cm depth, possibly due to lack of time and low infiltration rates into sub-soils that would carry dissolved calcium deeper into the soil profile. Infiltration rates were also increased by both perennial grass cover and mulch/compost on the soil surface, more so than gypsum in isolation. Therefore, amending soils to increase infiltration, reduce water runoff and promote grass growth will take a combination of both chemical and biological (organic) measures. However, due to limitations on the extent that infiltration can be increased in sodic sub-soils, managing excess surface water runoff will still likely be needed under ideal grass cover and soil conditions.

Fourth, base level conditions and downstream controls are important factors influencing headcut reinitiation into rehabilitated gully slopes. The driving force of rill initiation is water production and runoff from the upper slope, influenced by vegetation cover and infiltration. However, changes in slope at the base of inclines or in hillslope concavities can promote the initiation of headcuts during infiltration-excess overland flow. Headcutting can accelerate rilling and gullying through positive feedback loops until new equilibrium slopes are reached (Shellberg 2011; Shellberg et al. 2013b), assuming battered gullies are not regraded to slopes that are inherently stable (<1%). Therefore, the use of physical grade control structures (rock or wood) could be used to promote the stability of battered slopes, and used in combination with chemical and biological treatments. This was trialled at a neighbouring gully (CRGC1-40; Figure 97; Figure 98) with some success; however, headcuts and gullying up the new swale still attacked the slope and grade control structure. Stabilising battered gully slopes in sodic soil remains problematic even when a full suite of treatments is applied.

Despite both successes and difficulties in stabilising alluvial gully slopes with direct/intensive rehabilitation measures, the true challenge for this approach is the monetary cost of intervention. The total cost (commercial retail) of these intensive treatments ranged from $5000 to $6000 for 0.2 ha, which included heavy equipment hire and labour, gypsum, hydromulch, and fencing. Use of locally available compost and hand sown grass seed, rather than hydromulch, reduced this cost to ~ $3000 for 0.2 ha, but with slightly less effective results. Using local labour and machinery from individual properties could reduce costs further, along with government subsidies. Overall, it will cost $10,000 to $30,000 per hectare for direct/intensive gully treatment. Results from this study indicate that this type of direct intervention can reduce erosion rates by 50 to 60% during the first year (CRGC1-40; CRGC1-29), and perhaps more during later years, but not stop or eliminate gully erosion altogether.

Additional economic costs of direct/intensive gully rehabilitation are discussed in Section 8.2.

7.14 Gully Erosion along Cattle Station Dirt Roads and Tracks Traversing River Frontage with Dispersive or Sodic Soils

Improper road, track and fence location, construction and especially maintenance are some of the largest causes of gully initiation and acceleration on cattle station properties in northern Australia (aside from over-grazing on river frontage country). They are the easiest man-made erosion sources to identify and mitigate with erosion control measures. They should be a major focus for intervention to reduce cumulative sediment inputs at the catchment scale.

Gully erosion along unpaved roads can be reduced through implementation of road Best Management Practices (BMPs) to minimise excess water runoff, traffic disturbances, and annual maintenance such as grading. BMP guidelines for erosion and sediment control are readily available for construction sites and maintenance of large main dirt roads (Witheridge 2009; 2012; NSWOEH 2012). BMP guidelines are also available for general maintenance situations on cattle station roads and tracks in remote Australia (e.g., Herbert and Evans 1992; Hadden 1993; Jolley 2009; NTAA 2010). However, little documented information exists on how to best install, manage and maintain simple dirt roads and tracks in highly dispersive or sodic soils and steep river banks on river frontage in northern Australia, in order to reduce alluvial gully erosion initiation and acceleration. Much of the following is gleaned from existing BMP guidelines for dirt roads in northern Australia (Hadden 1993; Jolley 2009) and local observations in the Normanby catchment. Other road fact sheets have also been helpful (QDERM 2010b; 2010c).

7.14.1 Background on Cattle Station Roads on Highly Erodible Soils in the Normanby Catchment

On the more remote dirt roads and tracks of most cattle stations, local operators use machines (graders, front end loaders, bulldozers) to periodically grade and maintain their roads for easy access to remote parts of the property to manage cattle, as well as using roads and tracks as fire breaks. Most often these roads begin as simple tracks created by 4x4 vehicles over grasslands, often following earlier mustering routes that were travelled by horse. Over time, these simple tracks can be resistant to erosion if they are 1) put in stable locations, 2) not degraded by over use or inappropriate seasonal use, 3) kept well grassed, and 4), meticulously and lightly maintained and patched up only where occasionally needed by careful machine operators with allotted time and budget. Unfortunately, it is often the case that these tracks degrade over time due to the relentless attack of rainfall and runoff induced rill and gully erosion, concentration of water runoff along wheel tracks, and human negligence in terms of inappropriate road use, lack of maintenance or overzealous maintenance such as over-grading. Proper road placement or intervention early in the process of road erosion can often remedy the situation (Section 6.5.9), such as installing frequent and appropriately placed water diversion banks (whoa boys). Commonly however in the Normanby catchment, road erosion issues have surpassed easily repairable situations, and some repairs are on the verge of being futile.

Time, allocated budgets, and road/track maintenance plans and expertise are essential for proper road/track management and repair. However most commonly, station managers are confronted with annual business income pressures to quickly regain access to remote station areas after the wet season for the first cattle muster of the year. With limited time and budget, most often track and road maintenance consist of quick passes along roads with a grader, loader or dozer to essentially smooth over and fill in rills and gullies from the wet season so that a 4x4 vehicle can get through. These quick fixes undoubtedly result in increased sediment yields and road degradation over the long term. Rarely is enough time allocated to bring previously graded 'wind rows' back onto the road surface for crowning, install water diversion banks such as 'whoa boys', or address "hot spots" of major gully erosion threatening the road. Long-term planning and funding for road maintenance and erosion reduction is generally absent on cattle stations in the Normanby catchment and beyond. Furthermore, due to the cost and effort needed to properly maintain roads and tracks in highly erodible country, it is often seen by managers to be easier and cheaper just to continue grading down roads to maintain minimal access each year without addressing the actual cause of the road erosion. If the erosion situation becomes too large to quickly address with a machine, then it is deemed easier to just build a new road around the area and start anew with the same cycles of road creation, degradation, and sediment pollution. In order to remedy this negative feedback cycle, long-term road maintenance plans and funding are needed to address the causes of erosion and utilise BMPs that *both* maintain access and reduce the net erosion of soil.

Major structural intervention techniques applicable to large main dirt roads are likely not appropriate to the situation of small dirt roads on erodible soil in remote areas, due to both costs and the potential to actually increase erosion from major engineering works. This is especially true for roads that traverse dispersive or sodic alluvial soils on terraces/floodplains that are prone to alluvial gully erosion. Constructing wider and bigger formed roads with deep table and mitre drains can accelerate gully erosion on fragile sodic soils. A more measured approach is needed that combines the knowledge of more standard road BMPs to reduce erosion (e.g., Hadden 1993; Johansen et al. 1997; Jolley 2009; Witheridge 2009; 2012; NSWOEH 2012) with the knowledge of erosion processes, management issues and erosion control strategies associated with sodic alluvial soils (e.g., Section 2; Shellberg 2011).

As a generalised approach for roads on dispersive or sodic soils, localised road erosion issues should be patched up each year following well-considered road maintenance plans. Soil disturbances such as deep grading or cutting roadside ditches should be minimised. Old windrows from grading should be used to rebuild the road surface and/or construct water diversion banks. Grass vegetation and root cohesion on and along roads should be encouraged by slashing the road rather than grading. Water diversion banks (whoa boys) should be installed frequently based on slope (10-15m down steep banks) to divert water into stable dissipation sites. On steep banks at creek and river crossings, exposed sodic soils and water diversion banks should be armoured with non-sodic rock material from local sources to ensure that surfaces are not cut through or breached by rilling during heavy rainfall, cattle tracks (pads), and motor vehicle wheel ruts. Rock sheeting sensitive erosion prone areas on flats also will reduce runoff concentration and erosion. Application of this approach needs to be contained within a larger framework of 'adaptive management' that trials different intervention actions, measures and assesses the outcomes, and adapts future actions to lessons learned.

"*The washout is the result and not the problem; Reinstate the natural flow direction as often as possible*" (Darryl Hill in 'Erosion in the Savannah Rangelands'; Jolley 2009).

Since it is currently unclear what the most appropriate BMPs are to maintain road access while actually preventing or reducing erosion along station roads and tracks that traverse dispersive or sodic alluvial soils and steep river banks, several road stabilization and erosion reduction trials were conducted along the Granite Normanby road through a major concentrated areas of alluvial gully erosion (Figure 14; Figure 38; Figure 130; AGSO 1995). These trials will highlight the nature of the severe erosion problem, and through experiential learning from successes and mistakes, will provide some possible ways to address the erosion problem into the future at a larger scale. Or in other words, can gully erosion along roads through highly erodible country actually be decreased through investment in BMPs, or does this type of investment not make sense in terms of both economics and effectiveness of sediment reduction efforts, regardless of the gains or losses in road access?

7.14.2 Literature on Spacing of Water Diversion Structures on Highly Erodible Soils

The primary cause of erosion on dirt roads is excess and accelerated water runoff down the road or road ditch, which is a result of 1) poor road placement, 2) poor road design, 3) road entrenchment due to excessive grading and erosion, 4) excessive or inappropriate road use or season, 5) lack of good road surface material such as angular rock or gravel, and especially 6) no or infrequent water diversion structures (banks, whoa boys, culverts, dips).

For water diversion structures, the recommended spacing is usually determined by slope and soil erodibility classes (e.g., Johansen et al. 1997; Copstead et al. 1998; Jolley 2009; Witheridge 2009; 2012; NSWOEH 2012), as well as climate and expected rainfall-runoff intensities. On roads with low slope and low soil erodibility, recommended diversion structure spacing can average every 100m, depending on site specifics. However for steeper roads on highly erodible soils (i.e. sodic silt/clay soils on steep river banks), recommended diversion spacing should be reduced to <<30m and on the steepest erodible slopes be placed every 10 m (Table 7). This is especially true for soils and roads with low infiltration capacity and high rainfall intensity tropical climates, where water runoff production per unit areas can be extremely high.

Table 7 Recommended water diversion bank spacing (m) on highly erodible soils by Johansen (1997), Copstead (1998), Jolley (2009), NSWOEH (2012). The most detailed and reliable data comes from Johansen (1997) and Copstead (1998).

Soil Type	High Soil Erodibility	High Soil Erodibility	High Soil Erodibility
Source	Johansen et al. (1997) Copstead et al. (1998)	Jolley (2009)	NSWOEH (2012)
Slope (%)	**Bank Spacing (m)**	**Bank Spacing (m)**	**Bank Spacing (m)**
1	30 m	130 m	20-30 m
2	29 m	90 m	20-30 m
3	28 m	75 m	20-30 m
4	26 m	65 m	20-30 m
5	25m	60 m	20-30 m
6-10	23- 17 m	40 m	20-30 m
11-15	14-11 m	30 m	20-30 m
>15	10 m	15 m	20-30 m

Water diversion structures on roads can take many forms, including raised earth or rock banks (whoa boys), drivable dips, mitre drains (table or V-drains), and culverts to drain water from road ditches. Road cross-section shape can also promote improved drainage (crowning), but on flat terraces and floodplains caution is needed not to build up the road surface too much and actually block and divert natural flow paths. On basic dirt roads on cattle stations located on dispersive or sodic soils, periodic water diversion structures such as earth or rock banks (whoa boys) are the most appropriate structures to divert excess road runoff away from roads. Heavy grading or reshaping roads on sodic soils should generally be avoided except for extreme situations, due to the potential to enhance rill and gully erosion, rather than impede it. Rather, placement of frequent earth or rock diversion banks on native soil should be emphasised, in addition to capping banks and sodic road surfaces with local or imported coarse angular rock and gravel.

Water diversion structures made of earth or rock (whoa boys) should be at least 0.5 m high and 6+ m long (Figure 127). They should be permanent rolling humps that are drivable by large trucks (e.g., tip trucks). Some examples are included below (Figure 132b; Figure 134ab; Figure 138e; Figure 139b; Figure 140f; Figure 145). They should not be sharp crested or be able to be graded through by inexperienced operators. They should also be resistant to rill erosion and breaching by cattle tracks (pads), which frequently follow existing roads and fences.

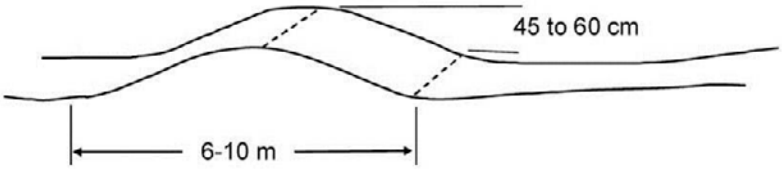


Figure 127 Recommended dimensions of water diversion banks (whoa boys) used frequently to divert water off roads (from Bartlett 1991).

7.14.3 Case Study 13: The Granite Normanby Dirt Road System

7.14.3.1 *Extent of the Road Erosion Problem along the Granite Normanby*

The sodic soils on alluvial terraces of the lower Granite Normanby River, near and upstream of the West Normanby confluence, are a major concentrated area for alluvial gully erosion (Figure 130). The area has the highest density of both alluvial and colluvial gullies in the Normanby catchment (Figure 14; Figure 15; Figure 38), and likely Cape York Peninsula outside the Mitchell catchment (AGSO 1995; Shellberg 2011). Where dirt roads have been located through this floodplain terrain riddled with alluvial gullies, “hot spots” of major accelerated gully erosion have been created that threaten the integrity and drivability of the road and increase sediment yields. Numerous quick fix attempts to maintain road drivability through these areas using graders and loaders have resulted in the net degradation of the roads through negative feedback cycles of gully erosion (Figure 128). Relocating roads after serious erosion is also common, which most often just moves the problem from one location to another creating cycles of degradation (Figure 129). These represent Worst Management Practices (WMPs). Rarely have the actual causes of erosion at any given road gully been addressed with adequate analysis and resources, nor have any Best Management Practices (BMPs) been utilised to remedy the situations.

Along 85 km of mapped dirt road in the Granite Normanby area, 154 major gullies associated with these roads have been identified and mapped (Figure 130). This is a minimum. Most often these gullies are associated with roads crossing creeks and rivers where the road drops over steep alluvial banks prone to gully erosion. In other locations gullies have migrated laterally into roads from both directions, fuelled by concentrated road runoff that eventually threatens the road. Along the 30km of main dirt road up the Granite Normanby floodplain valley (Figure 130), there are 11 major choke points where gullies are threatening basic road access (e.g., Figure 128d; Figure 133a; Figure 134c), and another 60+ road gullies that make drivability difficult (e.g., Figure 136; Figure 138; Figure 139; Figure 140).

The costs of maintaining this road network and accelerating erosion need to be weighed up against benefits of access and potential alternative routes less prone to erosion. Property planning and large-scale “Road Maintenance and Abandonment Plans (RMAPS)” are needed to cumulatively address these access and erosion issues.


a) b)
c) d)

Figure 128 Examples of road erosion conditions along the Granite/West Normanby valley where a) a road has been cut up a steep river bank with no erosion control, b) an old degraded road cut on a creek bank has been eroded by gullies, c) a road on the flat floodplain has been graded too deep causing water to concentrate and funnel into alluvial gullies, and d) a road has been choked on both sides from alluvial gullies that are partially fed by excess runoff along the road.

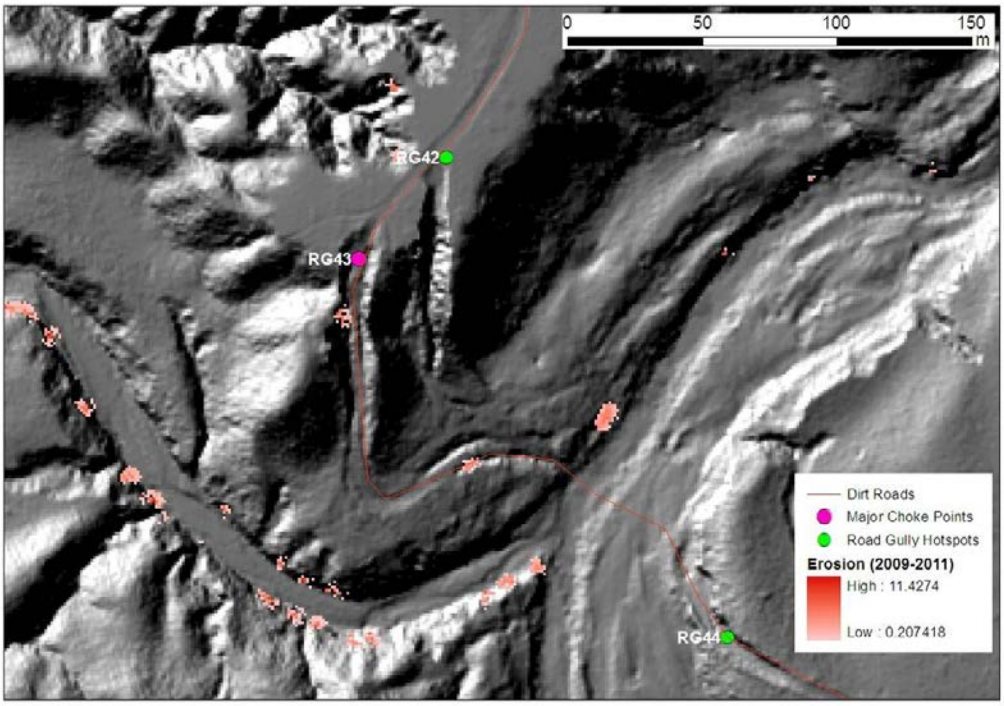
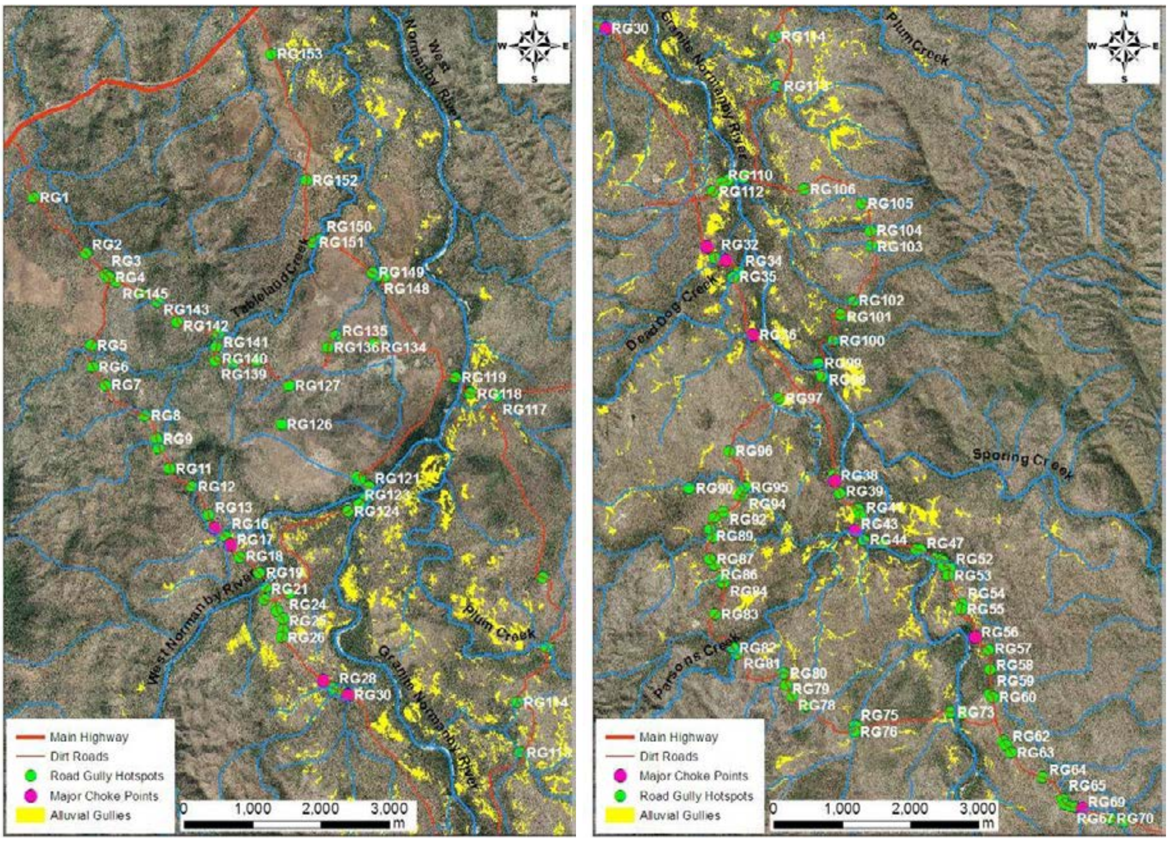


Figure 129 Multiple road cuts over a steep river bank that have initiated deep gully erosion. Note the abandonment of old road cuts (RG42) and the eventual need to abandon new roads cuts (RG43) due to active erosion.



a) b)

Figure 130 Maps of dirt roads, road associated gullies, major road choke points due to erosion, and the minimum distribution of alluvial gullies mapped from Google Earth (Brooks et al. 2013) at a) the area surrounding the West/Granite Normanby River confluence and b) upstream on the Granite Normanby River toward Parsons Creek. Note that map a) is located immediately north of map b).

7.14.3.2 *Granite Normanby Road Drainage Improvement: Qualitative Examples*

Two different trial sections of the Granite Normanby Road south of the West Normanby River were selected for road drainage improvements. On 2.0 km of treated road length, thirty (30) water diversion banks (whoa boys) were installed in Dec 2012. The goal was to test their functionality in highly eroded terrain to safely divert excess road runoff from the road away from gully heads, to reduce overall erosion and increase road stability. Management of concentrated water runoff along long fetches of road length addresses the primary cause of gully erosion. Frequent division and safe disposal of excess road water should be conducted before other complementary structural approaches to gully control, such as grade control structures, slope battering, gully infilling and revegetation. Otherwise these measures could be threatened by excess water runoff driving erosion. However the applicability of these types of measures to small roads in highly erodible, gullied terrain was partially unknown before these trials.

Four (4) large road cut banks were selected for detailed erosion quantification using terrestrial laser scanning (TLS), before and after installation at control and treatment sites (see Section 7.14.3.3 below). Other sites reviewed below were only qualitatively assessed using before and after observations and photos.

Material for water diversion bank construction came from local silt/clay soils (variably sodic) excavated from small pits adjacent to the road that also served as water and sediment dissipation ponds. Where needed, additional non-sodic rock gravel material was also imported from borrow pits to help construct diversion structures (Figure 131). Construction works were primarily conducted with a large backhoe with a 4-in-1 front bucket. A tip-truck supplemented rock material.

Commercial hourly rates for the large backhoe were $135/hr while the tip truck was $110/hr. Simple water diversion banks constructed with local native material took on average 1 hour each to construct properly at a cost of ~$150 per structure, to ensure proper location, angle, height, and functionality. More complex water diversion structures utilizing imported rock on steep gullied road cuts took on average 2 hours each to construct properly at a cost of ~$400 per structure including the tip truck costs. Assuming materials are accessible and project designers and machine operators are well prepared, it would take on average of 4 hours per road gully hot spot to install 3-4 frequent water drainage structures, cap the road surface with imported non-sodic rock, partially reshape the road, and ensure that sediment yields do not actually increase as a result of construction. Extrapolating this, it would cost a minimum of $154,000 to address all 154 gully hot spots in the Granite/West Normanby floodplain area assuming two machines (tip truck and large backhoe) at $250/hr total. Realistically this could be doubled due to the remoteness of the area, accessibility of rock material, contractor inflation, and the real need to conduct a careful job to ensure a reduction in sediment erosion along roads rather than acceleration at the cumulative scale. This is why several road stabilization and erosion reduction trials were conducted to assess the erosion reduction effectiveness and costs of intervention measures.

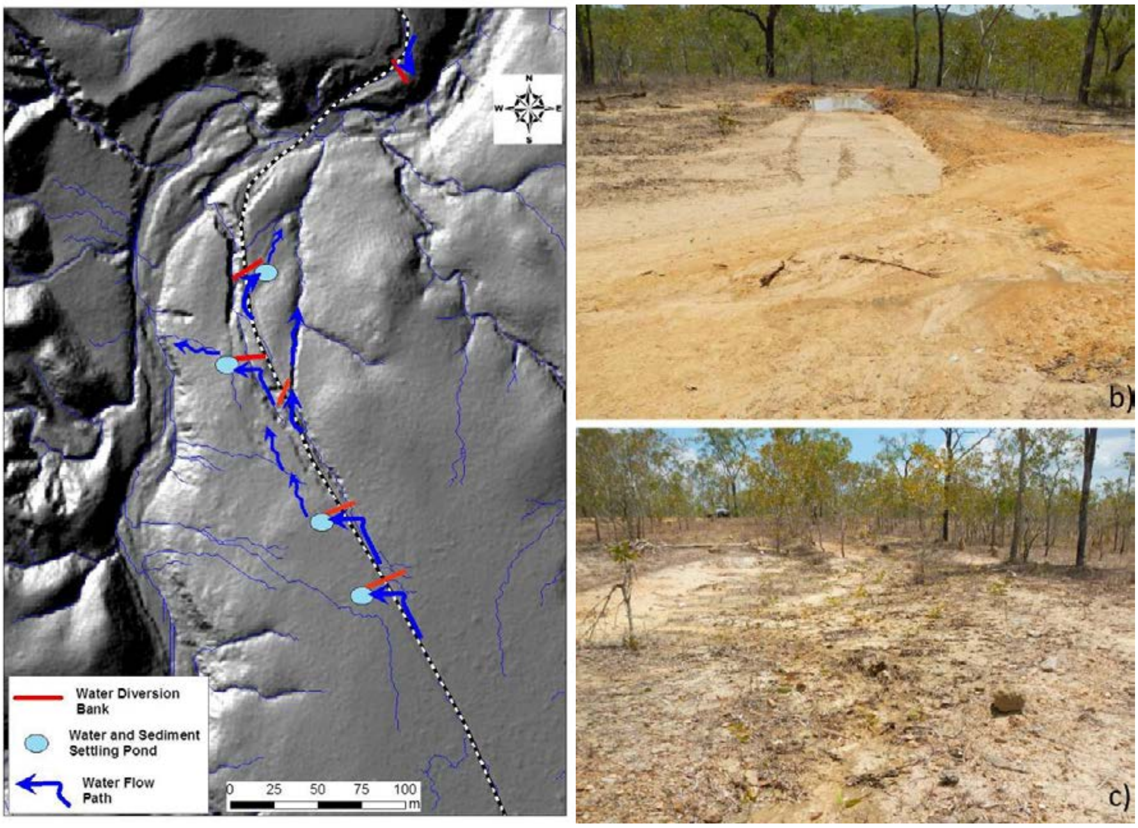
Due to the remote location of the Granite Normanby, gravel capping for road surfaces and diversion banks had to be sourced locally. Unfortunately, the only local source of rock material within 10 km from road gully sites was from ridgelines of the Hodgkinson Formation, which consist of slightly metamorphosed greywacke, siltstone, sandstone (Figure 131). Gravel to cobble sized rock is easily sourced from these ridgelines using bulldozers, however upon disturbance much of the parent material partially breaks down into finer grained constituents of sand and silt. Thus by using this material for road surfacing, undoubtedly much sand and silt is imported in the process. However, the finer matrix material can help lock larger gravel and cobble in place, and this material tends to hard set after several cycles of wetting and drying despite the continued vulnerability to rilling and sheet wash flushing away the fines. Depending on the outcomes of these different road stabilization trials (see Section 7.14.3.3), it could be recommended to not utilise this material into the future for road works due to its poor quality and pollution potential. This would mean, however, that better quality rock would need to be imported from longer distances increasing stabilization costs.


a) b)

Figure 131 Borrow pit material used for road surface capping and water diversion bank (whoa boy) construction originating from the Hodgkinson Formation meta-sediments (slightly metamorphosed greywacke, siltstone, sandstone). Note poor quality of available material and high percentage of fine sediment.

Several qualitative examples of water diversion banks are included below. At RG35, five (5) diversion banks were installed down a long 350 m road fetch (Figure 132a). Previously, concentrated water runoff down the road caused major gully erosion along both sides of the road before eventually delivering sediment into Dead Dog Creek. After construction of the diversion banks, the road runoff was diverted into several small ponds, where the coarser sand would settle out (Figure 132b). After several large rainstorms in Jan-2013, it became evident that these settling ponds were overwhelmed with water runoff and discharged water as sheet flow below the ponds. This water continued as sheet flow (Figure 132c) or concentrated flow in previous channels toward the main creek (Figure 132a). The wide, dissipated sheet flow did not appear to have the energy to create new gully erosion, but did erode additional surface soils. Overall, these initial results indicate that water diversion banks need to be more frequently spaced to be truly effective at dissipating and retaining road runoff along sodic soils with low infiltration rates. The average spacing of 50m per structure at RG35 should have been reduced to less than 25m to be truly effective at dissipating water along this road on sodic soil at 5-10% gradient (Johansen et al. 1997). On steeper sodic soils in the area, it is recommended that water diversion banks are placed even more frequently, for example, every 10-15 m on erodible slopes of 15% (Johansen et al. 1997; Jolley 2009; NSWOEH 2012; Table 7). This was done at experimental sites discussed below (see Section 7.14.3.3).

Several additional examples of fairly standard water diversion banks (whoa boys) are included in Figure 134a and Figure 134b.



a)

Figure 132 Improvements to road drainage at RG35 next to Dead Dog Creek a) mapped in planview using a LiDAR hillshade with derived flow lines, with examples of b) a ‘whoa boy’ water diversion bank constructed from locally borrowed soil material excavated from a small settling pond, and c) an overland sheet flow path derived from the outlet of a settling pond eventually flowing into the creek.

A very different scenario was present at RG30, where a major road choke point was created by two large alluvial gullies attacking the road location from either side (Figure 134a). Initial intuition was to either install large rock grade control structures at the gully heads, fill the gullies, or batter back the entire area (lowering the road surface) and creating a new road prism. However before any of these actions were taken, the degree to which water runoff down the road off the very flat floodplain was feeding the gully heads needed to be assessed and remedied. Assessment of the subtle topography of the situation indicated that the headcuts were migrating up toward the flat floodplain along the road. Therefore, two water diversion banks and adjacent settling ponds were constructed upslope of the headcuts (Figure 134b). During Jan-2013, the area was observed during a heavy rainstorm. Intense rainfall and low soil infiltration capacities on the fairly flat floodplain created sheets of overland water runoff that concentrated down the road. Initially, the diversion banks and settling ponds worked well to divert water off the road away from the headcuts. However upon additional rainfall, the structures were overwhelmed with water (Figure 134c). Water flowed out of the ponds and continued downslope, and eventually the shallow diversion banks were also over topped by water backing up behind them. This water eventually fed into the headcuts, albeit at a reduced rate compared to before the structures were installed (Figure 134d). To remedy the water runoff situation at RG30 before any additional structural efforts are targeted at the headcuts, much larger and more frequent water diversion banks are needed that divert overland runoff further away from the road to safe disposal locations. This will address part of the cause, rather than just the symptom.

a) b)

c) d)

Figure 133 A major road choke point at RG30 where a) gully headcuts threaten the road from either side, b) water diversion banks (whoa boys) were installed to divert water off the road and away from the headcuts, looking downslope, c) water runoff down the road during a major rain storm filling the diversion banks and pits, looking downslope, and d) water runoff down the road bypassing and over topping the diversion banks and continuing to feed the gully headcut.

More complex situations are often encountered along the heavily gullied terrain of the Granite Normanby that will take considerable effort to remedy if the road location is going to be continued to be used. At other major road choke points created by large alluvial gullies attacking the road location from either direction (Figure 134c), it would take major slope battering and engineering works to try and stabilise deep (5+ metres) alluvial gullies. These works still might not stabilise the gully and perched roads, and most likely will re-erode and actually increase net long-term sediment yields to downstream water bodies. From past local efforts, interim measures such as sheeting the road surface with rock gravel have slowed the headcut migration into the road surface. This is a result of increased surface protection of the soil from raindrop impact, reduced concentrated flow on the road due to minimised rilling, reduced piping of concentrated water into the road, and increased diffuse flow off the road that drips over the edge in numerous locations. This technique of sheeting the road surface with rock at gully choke points was trialled in several places (Figure 134c RG36, RG30) in order to make more informed decisions on its effectiveness. However, true fixes for the erosion and road access issues remain elusive, as there are few places to reroute the road due to dense gullied terrain (Figure 130). Relocating the road outside the Granite Normanby valley would be most logical.

At another complex situation (RG32), a large gully headcut was migrating into the road location on an alluvial fan inset within a creek valley (Figure 134d). Water fed the gully from three directions across the alluvial fan and was collected down both road approaches. To reduce the water supply to the headcut, long water diversion banks were installed across the road on either side of the headcut. Surface evidence after several rainstorms indicated that the diversion banks were effective at diverting 1/3 of the water runoff. However, water continued to feed the headcut from the centre of the alluvial fan (Figure 134d), and diverted water around the headcut continued onward to the local creek potentially accelerating gully erosion in other locations.

a) b)

c) d)

Figure 134 Examples of road improvements along the Granite Normanby road including a) a water diversion bank at the top of a creek approach, RG28 , b) a diversion bank along a long road fetch, RG29, c) gravel sheeting over a narrow road choke point (RG36) to protect the underlying sodic soils from wash and reduce ponding and piping, d) a water diversion bank (in background) used to divert some (1/3) but not all of the runoff water away from this road headcut, RG32.

7.14.3.3 *Granite Normanby Road Cut Stabilization: Quantification Experiments*

Along the main dirt road through the concentrated area of alluvial gullies along the Granite Normanby River (Figure 130), a short-term, rudimentary before-after control-impact (BACI) study design was conducted to quantify the erosional differences between four (4) different road cuts over steep, sodic, alluvial banks at creek approaches. Sites were surveyed with high resolution terrestrial laser scanning (TLS) of the soil surface after treatment in Jan-2013 and after the wet season in April-2013.TLS surveys collected hundreds of thousands of elevation points across at each road site, with point spacing less than 100mm. Erosional volume changes over the wet season were compared between treatment and control sites. Each site was also equipped with time-lapse cameras to photograph rainfall and erosion conditions multiple times per day. Rainfall was also measured at a central location within 3km of the treatment and control sites (Figure 135).

One road cut site was left as a control (RG33), while two others (RG 27, RG 31) were treated with water diversion banks (whoa boys) and surface capping with locally sourced, poorly sorted gravel and fines (Figure 131), while the other (RG106) was just treated with water diversion banks using native material but without surface capping. Two additional nearby road cut sites also can be used as a qualitative control to assess the degree and style of erosion associated with annual grading without BMPs.

Quantitative Comparison of Road Cuts Using Terrestrial Laser Scanning (TLS)

- Control (RG33): No treatment, status quo, annual grading end wet season
- Treatment (RG27): Water diversion banks, full surface capping with rock
- Treatment (RG31): Water diversion banks, partial surface capping with rock
- Treatment (RG106): Water diversion banks only.

Other qualitative controls

- Control (RG73): Steep river bank, newly graded road August 2012, no BMPs.
- Control (RG120): Steep river bank, newly graded road January 2013, no BMPs.

Due to the uniqueness of each site in terms of erosion patterns, the exact comparison of treatment and control sites is difficult and should be conducted with caution. However, major changes associated with road drainage improvements, and their success or failure, should be evident. The results from the TLS surveys also will highlight the exact erosion processes and the vulnerability of specific areas to sheet, rill, and gully erosion.

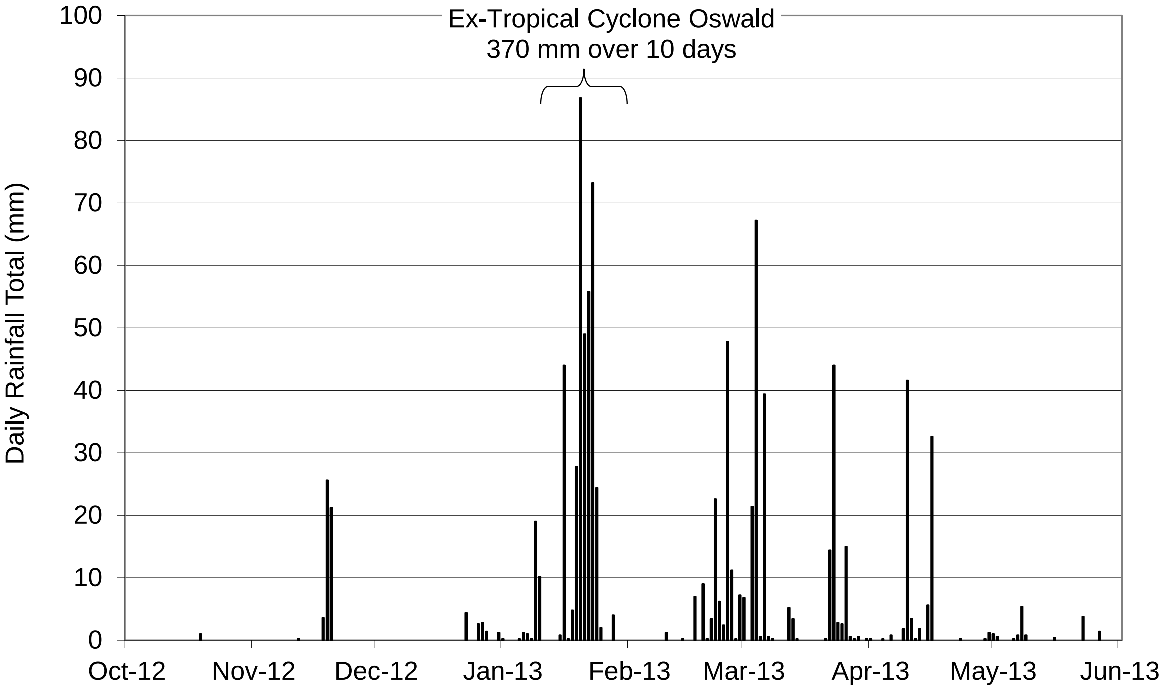


Figure 135 Daily rainfall totals during WY 2013 at Dead Dog Creek, Granite Normanby River (annual rainfall = 915 mm).

At the control site (RG33), regrading of the road cut approaching the creek crossing is conducted annually (Figure 136). This is similar to many other sites along this road network where deep gullies form every year and are regraded (Figure 128; Figure 129; Figure 130; Figure 137). Annual regrading is often just enough to get 4x4 vehicles through for property and cattle maintenance. Rills and gullies are filled in, and no BMP structures or actions are taken. Each year during the wet season, the road re-erodes via rilling and gullying making driving difficult (Figure 136a,c,d,e,f). This cycle has continued incrementally for decades, resulting in a deep and eroded road cut. Over the 2012/2013 wet season after 915mm total rainfall (Figure 135), deep rills and gullies had reformed at this control site, making vehicle passage almost impossible (Figure 136e,f). Quantification of erosion volumes using TLS surveys is discussed below.

a) Before (Aug 2011)

b) Before (July 2012)

c) Early Wet (Jan 2013) d) Early Wet (Jan 2013)

e) After Wet (April 2013) f) After Wet (April 2013)

Figure 136 RG33 road gully "control" site in a) Aug-2011 after an average wet season, b) July-2012 after typical annual regrading, c) & d) in Jan-2012 after several rainfall events that reinitiated rilling and gullying, and e) & f) in April 2013 after the wet season (850mm rainfall) and before any regrading.

Figure 137 Deep gullies formed annually during the wet season down steep road cuts in sodic soils can be difficult to regrade and fill in using heavy machinery, with very short-term access benefits.

At RG27, a road cut and creek approach previously concentrated road water runoff down the slope (Figure 138a) feeding several lateral gully headcuts (Figure 138b) in addition to the creek. Four (4) water diversion banks were carefully placed down the slope using a 4-in-1 bucket loader. A diversion bank was installed at the very top of the slope (behind photographer in Figure 138c) as well as at the first gully drain to the left. This gully drain was reopened to divert water from the top of the slope and prevent concentrated gullying further down slope. However, this gully receives less runoff from a smaller area than it did in the distant past due to installation of a diversion bank. It could be armoured with more rock at its head into the future, but damming it with a berm could redivert water down the road. Rock gravel was placed in this gully channel to dissipate energy, which needs to be enhanced in the future into larger check dams as erosion continues. Further downslope, a gully headcut threatening the road prism (Figure 138b) was excavated, old dysfunctional rubber tyres were removed, the hole was backfilled with coarser rock and gravel, and a diversion bank was placed at its head to divert water away from the headcut (Figure 138d). Further downslope, additional diversion banks were installed to divert water off the road. The entire road surface except for the very top was sheeted with rock gravel to protect the underlying sodic soils from erosion.

Over the 2012/2013 wet season (750mm rainfall after construction; Figure 135), surface rill and gully erosion were fairly minor at RG27 (Figure 138c-f) compared to other control and treatment sites, especially where sheeted with rock gravel and water was diverted. The road was drivable both during and after the wet season without the need for post wet season grading. However, sheet wash of fine sediment associated with rock sheeting was evident. Minor but continued headcut erosion also occurred into the first diversion gully, despite reductions in water runoff (Figure 138e). Gully erosion also continued on the sidewalls of gullies not treated. Quantification of erosion volumes using TLS surveys is discussed below.

a) Before Treatment (Nov 2012)

b) Before Treatment (Nov 2012)

c) After Treatment, Before Wet (Jan 2013) d) After Treatment, Before Wet (Jan 2013)

e) After Treatment, After Wet (April 2013) f) After Treatment, After Wet (April 2013)

Figure 138 RG27 road gully “treatment” site showing a) before treatment (Nov-2012) with runoff directed straight down the road into a lower gully, b) before treatment (Nov-2012) with headcuts working into road and attempts to stabilise with tyres, c) after treatment (before wet; Jan-2013) with 4 water diversion banks that drain water from much smaller areas of the road into adjacent gullies, d) after treatment (before wet; Jan-2013) of headcut with coarse rock (tyres are cosmetic) and a diversion bank to drain water away from headcut, e) & f) after treatment and after wet season (April 2013) and 750mm rainfall.

At RG31, a road cut over the bank of the high floodplain concentrated road water runoff down the slope (Figure 139a) feeding a gully along the fence line in addition to eroding the road (Figure 139c). Four (4) water diversion banks were carefully placed down the slope using a 4-in-1 bucket loader (Figure 139bd). Due to the tight situation of the cut on a broader ridgeline, water diverted off the road drained into adjacent gully catchments with headcuts and could accelerate erosion there over time. However due to the spacing, small catchment area above each diversion bank, and different diversion locations, the erosion impact on any one gully location was reduced compared to the previous situation. At the main gully headcut on the road, a diversion bank was installed immediately above it to drain water away in addition to backfilling the headcut with rock gravel. Each diversion bank was armoured with rock gravel to protect the native sodic soil from erosion; but the entire road surface was not armoured with rock gravel.

Over the 2012/2013 wet season (750mm rainfall after construction; Figure 135), surface rill and gully erosion were reduced as a result of water diversion bank installation (Figure 139). The road was drivable both during and after the wet season without the need for post wet season grading. Diverting water away from the main headcut and capping it with angular rock promoted gully stabilization (Figure 139f). Capping diversion banks with angular rock prevented rill incision through the banks. Minor rill erosion continued however where the road surface was not sheeted with angular rock gravel. Sheet wash of fine sediment associated with rock capping also was evident. Gully erosion also continued on the sidewalls of the main gully not treated (Figure 139f). Quantification of erosion volumes using TLS surveys is discussed below.


a) Before (Nov-2012)


b) After Treatment, Before Wet (Jan-2013)


c) Before (Nov-2012)


d) After Treatment, Before Wet (Jan-2013)

e) After Treatment, After Wet (April-2012) f) After Treatment, After Wet (April-2012)

Figure 139 RG31 road gully "treatment" site along a fence line showing a) before treatment (Nov-2012) with runoff directed down road into lower gully, b) after treatment (before wet; Jan-2013) with 4 water diversion banks that drain water from much smaller areas of the road into adjacent gullies, c) before treatment (Nov-2012) with water directed down road and gully, d) after treatment (before wet; Jan-2013) with water diverted off road and away from gully to right, e) & f) after treatment and after wet season (April 2013) and 750mm rainfall.

At RG106, a road cut over the bank of the terrace concentrated road water runoff down the slope causing rill and gully erosion (Figure 140ad), which delivered sediment to the nearby Granite Normanby River and made driving difficult. Instead of just grading the road and smoothing over the rills and gullies in typical annual fashion (e.g., RG 32; Figure 136), four (4) large water diversion banks were pushed into place down the slope using a rubber-tyre bulldozer. Water runoff was diverted into adjacent gully catchments, albeit from smaller catchment areas above each diversion bank and not concentrated in one location. Local sodic soil from the cut bank was used to create the diversion banks, as well as soil from the lower floodplain bench. Diversion banks were not covered with angular rock gravel, but were rather left in their native state to assess erodibility without rock cover but with diversion banks.

Site visits following a rain storm in Jan-2013 (30mm) indicated that deep rilling had reinitiated immediately on the road slope (Figure 140c) and through some of the diversion banks (Figure 140f). However, the banks did function to divert most water off the road. On the lower slopes, diverted water was collected in two settling ponds; however in a few locations water bypassed these ponds as it cut around the other end of the diversion bank. By April 2012 after 750mm of rainfall following construction (Figure 135), deep rills and gullies had cut into the road and had breached through several of the water diversion banks (Figure 140d,h), making vehicle passage impossible. The sodic soils provided little resistance to raindrop impact, sheet wash, and rill and gully erosion, compared to other sites with gravel rock amour (Figure 138; Figure 139). Quantification of erosion volumes using TLS surveys is discussed below.

a) Before (Nov-2012)

b) After Construction (Jan-2012)

c) After Rain (Jan-2012)

d) After Wet Season (April-2012)

e) Before (Nov-2012)

f) After Construction (Jan-2012)

g) After Rain (Jan-2012) h) After Wet Season (April 2012)

Figure 140 RG106 road gully "treatment" site a) looking upslope before treatment in Nov-2012, b) looking upslope after treatment with bulldozer grading and installation of 4 water diversion banks in Jan-2013, c) looking upslope after one rain event (30mm) in Jan-2013 with rill initiation, d) looking upslope after the wet season in April-2012 (750mm rainfall) with deep rills and gullies, e) looking downslope before treatment in Dec-2012, f) looking downslope after treatment with bulldozer grading and installation of 4 water diversion banks in Jan-2013, and g) looking downslope after one rain event (30mm) in Jan-2013 with rill initiation, and h) looking upslope after the wet season in April-2012 (750mm rainfall) with deep rills cutting through diversion bank.

Quantification of erosion volumes using TLS surveys worked well on for the surface of each road cut. Erosion volume comparisons between control and treatment sites were restricted to the road surface only, due to inadequate survey coverage in adjacent convoluted gullies off the road surface. Digital elevation models (DEMs) were created using hundreds of thousands of TLS survey points and 5mm pixels. DEMs from before and after the wet season were differenced for specific index areas on each road surface. Index areas ranged from 190 to 250 m^2 and locations of the TLS machine setup (3^+ m dia) were cut out of the comparison to minimise error. Total net erosion (erosion and deposition) for each site was normalised by the index area to allow comparisons between sites (kg/m^2/yr). Additional comparisons were made using maximum (fill), minimum (scour), and mean erosion depths at each site, along with total net erosion.

Total net erosion at all sites was relatively high over the 2012/2013 wet season, with 18 to 40 tonnes per year eroded off each index area of the road cuts, which is a minimum for the total area of each road cut. These rates equate to 240 to 660 tonnes/km/year and 900 to 1600 tonnes/ha/year, which are very high on a world scale for both roads (Cederholm 1981; Reid and Dunne 1984; Sidle et al. 2006) and gullies (Shellberg et al. 2013b).

The control road cut (RG33) without BMPs had a net erosion of 93 kg/m^2/yr (Figure 141). The highest erosion rates were observed at RG106 treated with water diversion banks but no rock surfacing (158 kg/m^2/yr), but this was also the steepest road grade (19.6%). Most of this erosion was from the longest road section between banks where there was no location to divert water to. Sites treated with BMP diversion banks and various levels of rock surfacing (RG27, RG31) generally had similar net erosion rates (93-102 kg/m^2/yr) to the control site, which was unexpected (Figure 141). However, the processes of erosion at each site were very different (gullying vs. sheet wash).

The control (RG33) and earth bank only (RG106) sites experienced deep rilling and gullying due to lack of soil protection, with typical gully scour depths ranging from 0.5 to 1.0 metres deep (Figure 142). Gullying made these road approaches un-drivable by the end of the wet season. In contrast, road cuts treated with water diversion banks and rock surfacing (RG27,RG31) had maximum rilling depths less than 0.2m (Figure 142), which allowed the road to be drivable throughout the wet season with no need to regrade the road after the end of the wet season. The bulk of material eroded off these rock armoured slopes (RG27,RG31) was fine matrix silty sediment associated with the gravel source from the local pits (Figure 131). Raindrop impact and surface sheet flow winnowed these fine sediments from the rock surfacing, leaving a courser lag of rock material behind to continue to protect the soil surface for years to come. These armoured road surfaces (RG27, RG31) lowered on average 50 to 60 mm over the wet season, which is greater than the 15 to 25 mm per year eroded off the dirt sections of the Peninsula Development Road (Gleeson 2012).

These results highlight that using water diversion banks and rock armouring on steep road cuts can reduce deep rill and gully erosion, but will not necessarily reduce short-term (1 year) erosion rates. In some instances without rock surfacing, erosion rates can increase from intervention. Using rock armouring of diversion banks and road surfaces can switch the erosion process from rilling and gullying into predominantly raindrop impact and sheet wash erosion. If a poor quality source of rock is used for armouring, then short-term erosion rates can remain elevated until matrix fines are washed from the rock material. The degree that surface lags of coarse rock will provide longer-term protection against raindrop impact and sheet erosion remain unknown. This needs to be monitored at these sites during subsequent years. It is hypothesised that road surface erosion rates will decline below control-background levels once fine sediment is washed from the rock armouring and remaining coarse gravel lags continue to protect the soil surface.

The long-term success and the relentless attack of gully erosion will need to be monitored and addressed by adaptive management at these sites. This is especially true for associated gully erosion just off the road surface, which could be reduced or accelerated by diversion of water off the road surface. Overall however, these preliminary results indicate that *both* frequent water diversion banks and high quality rock amour are needed to reduce erosion on steep road cuts through sodic alluvial soil.

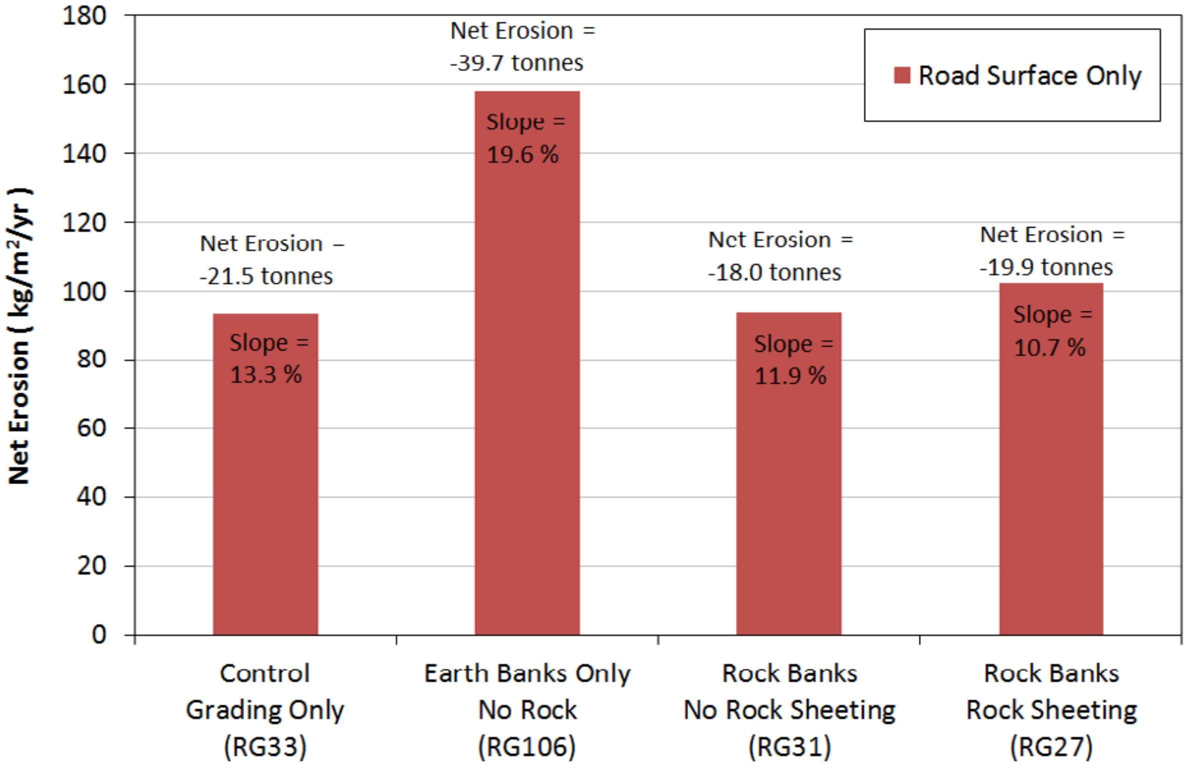


Figure 141 Net erosion (erosion plus deposition, kg/m^2/yr) at index sections of the four (4) road cuts monitored over the 2012/2013 wet season with repeat terrestrial laser scanning (TLS). Note that the measurements were calculated from hundreds of thousands of TLS survey points at each site.

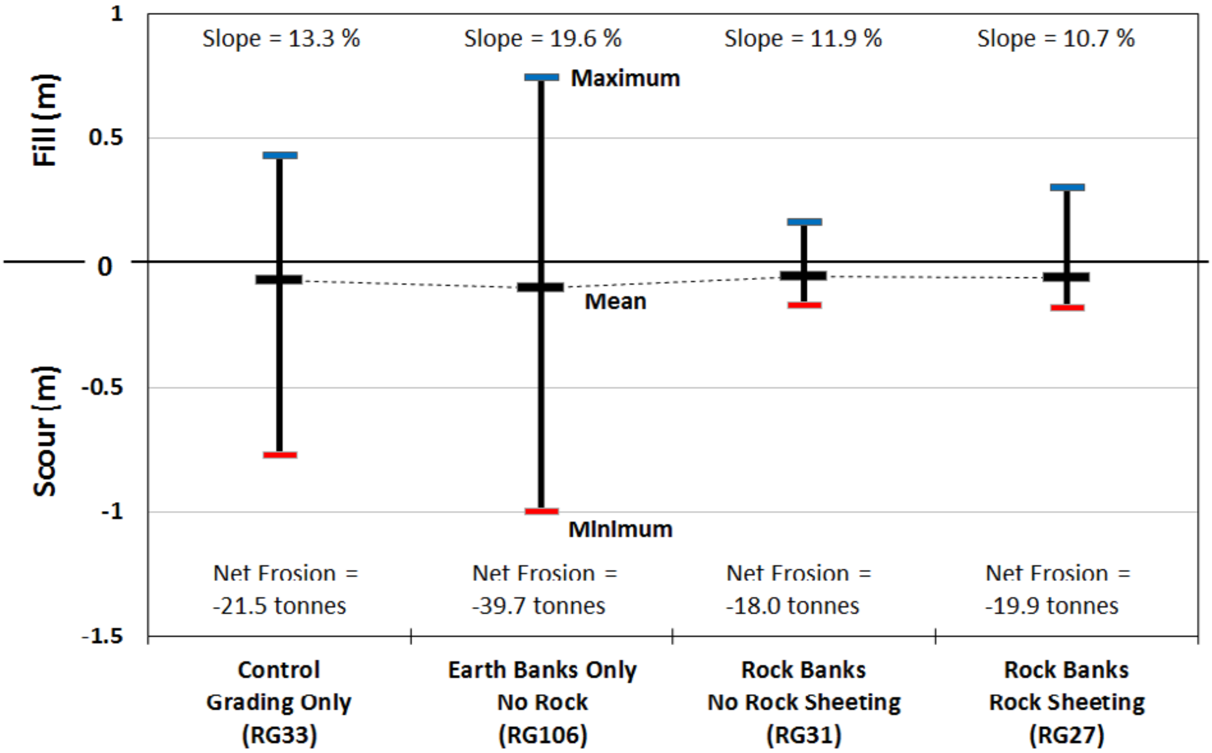


Figure 142 Maximum, minimum, and mean (average) sediment scour (erosion) and fill (deposition) values at the four (4) road cuts monitored over the 2012/2013 wet season with repeat TLS surveys. Note that the measurements were calculated from hundreds of thousands of TLS survey points.

7.15 Gully Erosion along Fence Lines Traversing River Frontage with Dispersive or Sodic Soils

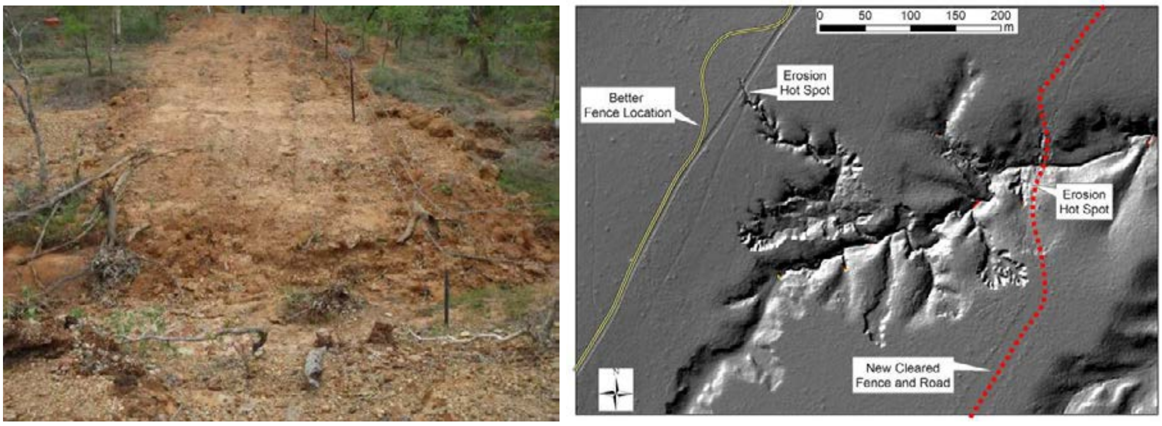
The intensive use of fencing to control cattle has increased on cattle properties in the Normanby catchment over the last 50 years and thousands of kilometres of fence line have increased erosion, especially when crossing dispersive or sodic soils along river frontage. Many fence lines are graded as fire breaks, used as roads, and cut by cattle tracks (pads), which can concentrate water and accelerate gully erosion (e.g., Figure 143; Jolley 2009; QDERM 2010a). The construction of fences through sodic soils along river frontage will invariably cause accelerated erosion and pose a long-term threat to infrastructure stability. Jolley (2009) provides erosion control details for fence lines on grazing properties in northern Australia. However, additional BMP guidelines and design details are needed for fencing on dispersive or sodic soils and across steep banks of creeks and rivers, where most erosion is concentrated.


a) b)
c) d)

Figure 143 Fence line crossings of a) a steep creek bank with sodic alluvial soils on a high floodplain, b) duplex soils (sodic sub-soils) through a creek on a terrace, c) colluvial soils of a hillslope creek crossing, and d) a steep slope cleared of vegetation regrowth with heavy machinery along a fence line. In all cases, fence construction and maintenance have caused rill and gully erosion from machine grading, lack of water diversion structures, and cattle tracks (pads) along fences over steep banks.

Proper fence placement *around* rather than through erodible alluvial soils (e.g., Figure 130) can minimise future erosion and prolong the life of the fence (Figure 143a). Fences should be located on stable soils and geology, such as on subtle ridge and spur crests between drainage catchments. Carefully planning fence routes will minimise the number of crossings of existing gullies, unchannelled hollows, creeks, and rivers, which will in turn reduce fence maintenance costs and rill and gully erosion (Figure 143; Figure 144). Basic soil/geology and erosion hazard maps can be useful for locating infrastructure during property planning, as well as topographic maps, Google Earth images, and high resolution LiDAR data where available. Subsequently after desktop planning, scouting and mapping the best routes for fences on the ground using motor bikes and GPS can help avoid erosion hazards and unnecessary use of large machinery. Once the most appropriate fence locations are determined, the use of best management practices (BMPs) such as water diversion banks, minimization of tree clearing and grass grading especially on steep banks, and using slashers and prescribed fire for fire breaks can reduce the potential for gully erosion along fence lines.

As an example of a poorly implemented Reef Rescue funded project in the Normanby catchment, a riparian fence along a river cut through rather than routed around several alluvial gullies and small creeks. The result was the acceleration of sheet, rill, and alluvial gully erosion along the fence line and associated new “road” (Figure 144). Grading and bulldozing the approaches to the creek/gully crossings increased erosion and was not mitigated by installing Best Management Practice (BMP) structures such as water diversion banks (whoa boys) and grade control structures. However, the most appropriate BMP would have been to route around the gully prone areas and not disturb them in the first place. This example highlights the sediment trade-offs between 1) constructing fencing infrastructure in the name of reducing sediment loads, *versus* 2) actually increasing sediment loads by poorly located, planned, designed, installed, and maintained fences and roads.



a) b)

Figure 144 Example of a riparian fence installed (with Reef Rescue funds) to reduce sediment erosion and water quality impacts on the local river that has actually a) accelerated sheet, rill, and gully erosion along the approaches to a small tributary creek due to b) poor road location planning, inadequate design, and no BMP structures.

Installation of frequent water diversion banks (whoa boys) during construction and/or ongoing maintenance of fences can minimise future erosion by diverting concentrated water runoff and can prolong the life of the fence threatened by gully erosion. The frequency of diversion banks depends on the slope, but banks should be placed every 10-15 m on steep or erodible soils. Large banks (>0.5m high; > 6m wide) will ensure long-term functionality and drivability, while preventing future machine operators from grading through them (Figure 145). Extreme caution is needed however for bank construction on steep erodible soils, as construction could actually accelerate erosion. Similar to roads on steep erodible slopes, banks at fence crossings might need to be capped with or constructed out of non-sodic soil/rock to armour the soil and prevent rills and gullies from cutting through them (Figure 145b). In many instances it is better not to disturb soils on steep erodible banks with machinery, and rather use alternative fencing methods such as fencing "tree-to-tree" without soil and vegetation disturbance (Figure 146).

a) b)

Figure 145 Examples of large water diversion banks (whoa boys) constructed along a terrace fence line by a proactive machine operator and functioning during a rainfall event. Note however, the spacing or frequency of the banks should have been increased (<50m) to minimise water volumes arriving and flowing/eroding around each bank.

Minimizing the amount of tree and grass vegetation cleared and graded during fence installation and maintenance can reduce gully erosion. This is especially the case for tree clearing and machine use on steep banks and slopes where fences cross hollows and creek or river channels. As an alternative to reduce erosion, existing live trees can be used as fence posts and strainers (tree-to-tree) on steep banks at crossings (Figure 146), which will avoid the need for tree clearing, soil disturbance, or installation of water diversion banks. This 'old fashioned' way of fencing can essentially leave the soil of erodible banks untouched. Manual repairs of fences in these areas might increase to remove down branches (Figure 146b), but these crossing areas often need regular hand maintenance anyway to annually repair 'flood fences'. However, long-term costs of grading, management of tree sucker regrowth, and repair of fences destroyed by gullies induced by construction disturbance will be reduced by using tree-to-tree methods over steep banks.


a) b)

Figure 146 Fencing “tree-to-tree” down steep banks at river, creek and gully hollow crossings can minimise ground disturbance and the need to clear vegetation.

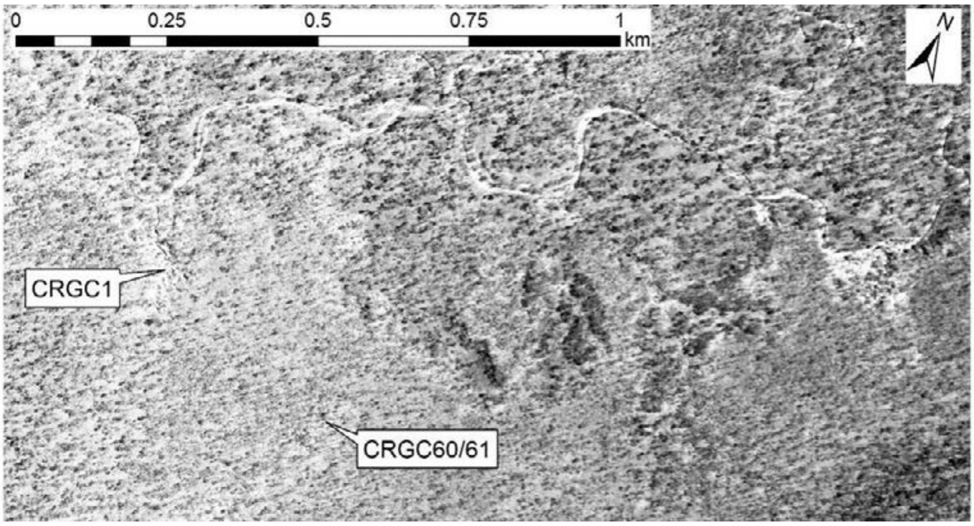
For fence lines used as fire breaks, annually grading fence lines to clear grass and sapling growth can accelerate erosion by removing vegetation cover and grass root cohesion, by grading too deeply and thus concentrating water flow, and by grading over or through water diversion banks rather than maintaining them (Figure 147). Indiscriminate clearing of tree growth with heavy machinery along fence lines also can accelerate rill and gully erosion (Figure 143d). Alternatives to graded firebreaks include slashing soon after the wet season or the use of herbicides to reduce grass and tree sucker growth (Jolley 2009). However, off-site pollution needs to be carefully avoided when using herbicides. Furthermore, the trash will either need to be burnt before the surrounding grass has dried out, mechanically raked, or thrown to one side of the break from multiple passes. The combined use of vegetation slashing or herbicide application together with early-dry season prescribed fires along fence lines using aerial incendiary flights could be an effective way of installing large fire breaks over remote country to prevent late-dry season intense fires (see Section 6.5.7).

Figure 147 Fence line grading for fire breaks can concentrate water runoff from deep grading and accelerate gully erosion, especially if frequent water diversion banks (whoa boys) are not installed to maintain natural flow paths and mitigate erosion.

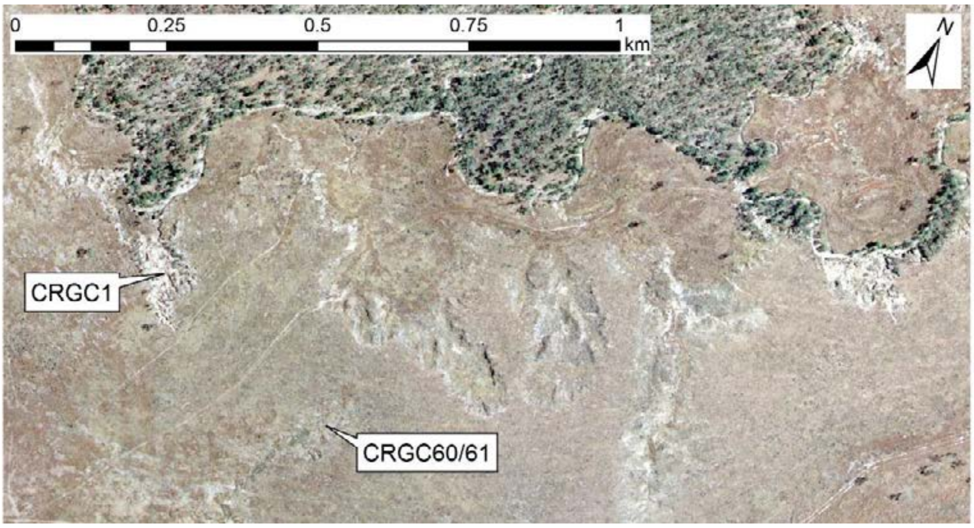
7.16 Gully Erosion in Tree Cleared (Pulled) Paddocks on River Frontage with Dispersive or Sodic Soils

Clearing of trees and vegetation has occurred on > 5000 hectares of distributed erodible river frontage soils in the Normanby catchment (i.e., Laura, East & West Normanby, Hann Rivers and tributaries), which excludes Lakeland where > 10,000 ha have been cleared on predominantly basalt derived soils (Grundy and Heiner 1994). Tree clearing can change the water balance by reducing water transpiration by trees, raising water tables, increasing sub-surface water seepage, and accelerating surface water runoff. Soil and vegetation disturbance from bulldozing, chaining, and stick raking vegetation, in addition to changes in the water balance, have the potential to initiate or accelerate alluvial gully erosion along creek and river margins. For example, historic clearing of trees within and above pre-existing floodplain hollows on terraces and river banks has promoted deep alluvial gully erosion into these features (Figure 45; Figure 96; Figure 148; Figure 149; Figure 150; Brooks et al. 2013). Clearing and chaining on steep slopes can also cause and accelerated erosion (Figure 147b). Generally, clearing trees from erodible soils on river terraces and floodplains of river frontage should be avoided. Where this has already occurred, mitigation measures can be instated to reduce the continuing or future erosion of alluvial gullies.

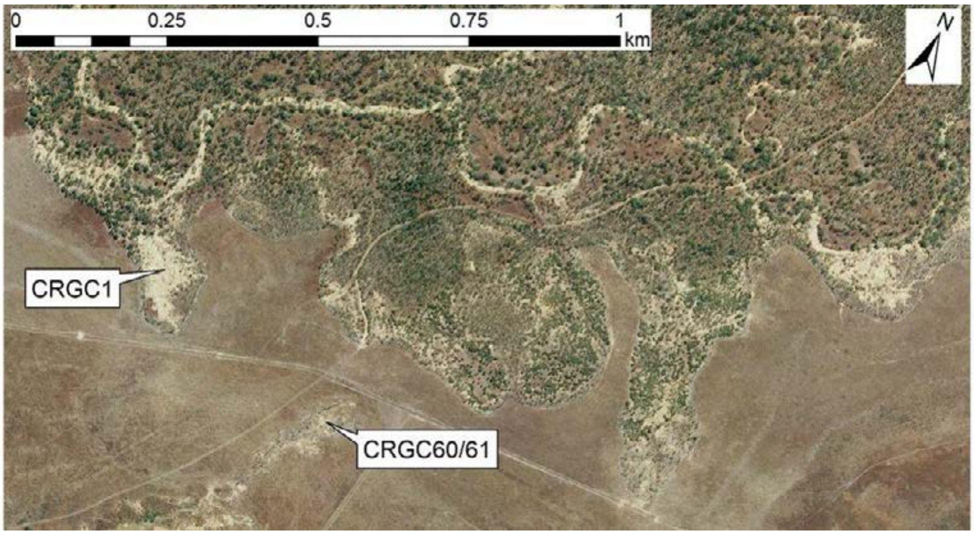
Many of these cleared river frontage paddocks are periodically recleared with machinery and heavy chains to reduce the regrowth of native tree species, notably *Melaleuca viridiflora* but also others. Ideally, other more sustainable measures are needed to control the regrowth of these trees (e.g., spelling, periodic fire, chemical weed control, pasture competition). However for short term gains on flat terrain under dry conditions, this machine chaining appears to cause minimal damage to the soil and perennial grasses, and promotes the growth of desired perennial pasture species if other weeds are also managed. However, accelerated gully erosion can occur where periodic reclearing and chaining is conducted through or alongside floodplain hollows, drainage depressions, gullies, creeks, and river banks, which can cause soil disturbance and enhanced water runoff (Figure 149; Figure 150). Water flow can concentrate down wheel ruts of heavy machinery, and fragile soils can be disturbed from machine roller tracks through gullies. Ripping trees out of the ground (dozing, chaining, stick raking) within hollows, gullies and creek banks can also disturb the soil and initiate rill and gully erosion. Residual berms of earth or cleared vegetation from machinery can divert and concentrate water flow into vulnerable erosion areas, but if designed and placed correctly they can also reduce water runoff into gullies and divert water to stable locations (Section 7.12). Furthermore, the proactive use of cleared wood for grade control structures within existing hollows and gullies could promote bed stabilisation if utilised correctly (Figure 77b; Figure 78b; Figure 80).



a) 1952 Aerial Photo



b) 1987 Aerial Photo



c) 2011 Aerial Photo

Figure 148 Aerial photograph history along the alluvial creek frontage of a tributary creek of the Laura River. Note locations of CRGC1 and CRGC60/61 study sites. Note the floodplain hollows and earlier phases of gullying where more recent accelerated gully erosion has developed.

a) b)

Figure 149 Tree reclearing and chaining through a) a 2m deep alluvial gully (Figure 45) on a river terrace and b) a 0.5m deep alluvial gully on a river terrace. Note that grass and tree vegetation buffers (+50m) should be installed around these features, especially Figure 149a, to allow for revegetation and to protect the gully from periodic reclearing of the improved paddock.

The best management practice along the margins of tree cleared paddocks on river frontage would be to install or retain grass and tree buffers along drainage lines, hollows, gullies, creeks and rivers, well back from breaks in slope of high banks (Figure 2). For small gullies and creeks, buffer widths should be > 50 m wide from the high banks of the waterway. For larger creeks and rivers, buffers should be >100+ m wide back from the high banks where alluvial gullies often initiate, and preferably encompass the local catchment area of gullies and hollows (Figure 2). In practical terms this could mean leaving uncleared buffers > 500m to 1 km from the centre of the creek or river channel (Figure 148). This will reduce the potential for alluvial gully initiation or propagation by minimising disturbance within the gully catchment area. Along river frontage in the Normanby catchment, modest riparian vegetation buffers were often retained along major rivers during the initial historic vegetation clearing. Some buffers have been allowed to regrow after overzealous initial clearing (e.g., Figure 148). However, buffers were not commonly retained along smaller tributary creeks, hollows and drainage depressions on floodplains, or gullies, which were unknowingly highly vulnerable to erosion (Figure 45; Figure 96; Figure 148; Figure 149; Figure 150). Main river buffers were also not wide enough to protect the full catchment area of alluvial gullies along river frontage (Figure 2).

As an example, if a vegetation buffer with cattle fencing had been retained during initial tree clearing in the 1970's around the alluvial gully at CRGC6061 (Figure 148; Figure 149; Figure 45; Section 7.5.2.2), then gully erosion into this small hollow would not have been so severe as a result of clearing, disturbance and vegetation changes. Therefore, by instating a +50m tree and grass buffer around this gully, along with cattle exclusion, it is hypothesised that the gully system will stabilise as indicated by preliminary data (Figure 46; Figure 47). Eucalyptus and Melaleuca tree regrowth will occur within the fenced area and possibly compete with grass understorey vegetation for light, nutrients, and water. However, trees can also help stabilise gullies (Shellberg 2011), and a balance between tree and grass vegetation cover will emerge over time without intense grazing pressure.

As another example, a vegetation buffer was not retained or reinstalled during (re)clearing of the Normanby River frontage paddock in Figure 150 below. A +50m vegetation buffer around the gully headcut would have reduced soil disturbance from machinery, clearing, and cattle tracks (pads) common along cleared margins (Figure 150). On the edge of this buffer (and/or near the gully scarp), an earthen berm or bank (Section 7.12; Figure 87; Figure 88) should have been installed to divert excess water runoff from the cleared paddock into a safe disposal point, such as a grass waterway or constructed pond on the floodplain (Section 7.12). Installing contour berms could also be appropriate on upslope sections of the cleared paddock (e.g., Figure 85), as long as the surface water runoff is managed appropriately and not diverted to steep creek banks and drainage lines where it could fuel more gully erosion. Proper best practice management of surface water runoff, erosion, and nutrient runoff will be especially important if future agricultural development (tilled pasture, bananas, leucaena, etc.) commences on these fragile river frontage soils next to major rivers and intact habitat.

Figure 150 An alluvial gully headcut at the margin of a recently (re)cleared paddock, fed by overland water flow from the clearing. At a minimum a water diversion bank should be placed around this gully, as well as a larger vegetation buffer (+50m). Regrading or tillage is not recommended without major intervention.

8 Social, Economic and Political Challenges to Alluvial Gully Prevention and Rehabilitation

This report has highlighted many of the physical challenges to cumulatively preventing and rehabilitating alluvial gully erosion at the catchment scale. To significantly reduce sediment loads, mapped concentrations of gully erosion and sodic soils of terraces along river frontages should be targeted for large-scale changes in land use paradigm. These changes should include cattle exclusion or intensive spelling, reduced intense late-dry season fires, weed control, altered road and fence use and construction, and long-term soil, biodiversity and carbon conservation. At a minimum this will prevent new gullies from initiating. However, changes in land use in key areas might not be sufficient on its own to reduce gullying enough to meet sediment load reduction targets. More direct/intensive intervention also will be needed at young, incipient gullies that are still developing, to prevent major erosion well into the future. Thus, combined indirect/passive and direct/intensive approaches will be needed to reduce anthropogenic sediment loads.

Achieving these physical actions will take significant social, economic and political will to overcome any real or perceived challenges.

8.1 Social Challenges

There are many social challenges to addressing alluvial gully erosion in the Normanby catchment on Cape York Peninsula. Major social factors that influence a cattle grazier’s relationship with the cattle and landscape include age, gender, property size, family history, education history, skills and experience, material wealth and financial security, work and lifestyle aspirations, values, religion, community norms and perceptions, social approval and acceptance, degree of isolation, and perceived benefits and costs of actions to social, economic and political factors (Figure 151; Bohnet et al. 2011; Pannell et al. 2006).

Many cattle graziers from historic grazing families on Cape York Peninsula care deeply about the landscape as well as their livelihoods and way of life. Their families have long known about alluvial gully ‘breakaways’ and their issues. Initially they find it difficult to accept scientifically quantified changes in erosion over time and historic land use impacts. However, upon realization of the problem and invoking their land ethic, they remain open to ideas on addressing the erosion to care for their country, but are economically restrained due to the low financial returns in the Cape York Peninsula cattle industry. These landowners have strong “stewardship & lifestyle” motivations (*sensu* Greiner and Gregg 2011), and thus are concerned about the issue but have no financial basis to act. They are open to government investment and incentives to address erosion for public benefit, and many have completed successful Reef Rescue cost-share projects that also benefit their property infrastructure (e.g., narrow riparian zones and fences that make mustering easier but maximise river frontage grazing). However, they are also concerned that major government investment or regulation could affect their business viability and long-term lifestyle (e.g., excluding or spelling cattle from river frontage). They want tenure and lifestyle security, and minimal government regulation, but also would be open to government or market-based payments for 'ecosystem services' derived from land use actions or zones of conservation (carbon, biodiversity, soil retention, weed and feral management).

On the other end of the social spectrum of cattle graziers in the Normanby catchment are relatively new graziers from afar who have purchased leases as investment properties. These landowners have strong "economic & financial" motivations (*sensu* Greiner and Gregg 2011), and generally have less developed land and soil conservation ethics. Because of realised low financial returns from their cattle properties, they are willing to accept government funding for erosion control even under cost share. However, their true interests are in property development investments to maximise returns or develop the property for resale. They also know they can inflate their cost share contributions with little governmental oversight on the actual implementation or effectiveness of erosion control projects, in order to profit from government investment. Their interest in long-term maintenance of invested infrastructure for erosion control benefits is minimal, unless there is continued government funding. Some have stated clearly that they do not care if they accelerate erosion or send sediment to the river or reef, as they have plenty of leased land and no intention of long-term ownership or stewardship. However, if approached with appropriate compensation packages to buy-back or destock large areas of their property for soil conservation, they would be willing to negotiate as short-term landowners in financial hardship or because of interest in reselling the property for profit.

Overcoming some of the social challenges with education, outreach and/or investment will be necessary to cumulatively reduce soil erosion. Government programs need to be based on an understanding of the aspirations of landowners and such programs should tailor conservation funding to match, in order to harness these intrinsic motivations (Greiner and Gregg 2011; Bohnet et al. 2011).

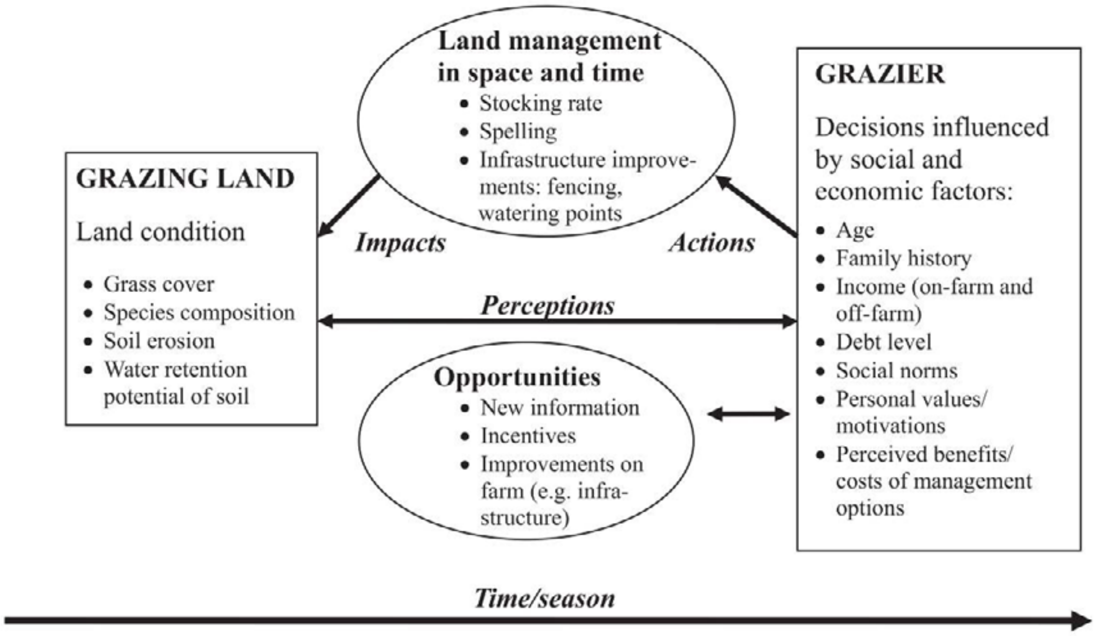


Figure 151 A conceptual model of the interconnected relationships between a grazier's social and economic situation, land management, and land condition (from Bohnet et al. 2011 with permission).

8.2 Economic Challenges

8.2.1 Cattle Grazing Economy on Cape York Peninsula

The status of the cattle grazing industry in the Normanby catchment and Cape York Peninsula has been in a state of transition for the last 20 years, with some successful properties and many that are struggling. The remote nature of the area, long distance to markets, extreme wet-dry climate, and relatively low productivity of the soils and grasslands have historically affected the nature of the grazing industry on Cape York Peninsula (Cotter 1995). Most grazing operations historically survived by grazing low densities of cattle over large areas of native pasture with minimal infrastructure development, variable and overhead costs. More recently, most properties have developed and intensified their grazing practices to some degree, through developments in introduced pasture (e.g., legumes), supplementation (e.g., protein, energy and mineral lick) and herd management (e.g., fencing and breeding) (Cotter 1995).

As both development and inflation have progressed, costs have gone up for both variable costs (labour, shipping transport, materials, feed, vaccination, animal purchase, fuel, electricity, etc.) and fixed costs (salaries, depreciation, maintenance, equipment, interest payments, property rates etc.). Returns from the sales of cattle have not always been commensurate with increases in fixed and variable costs. For example, while grazing regime, animal quality and time of cattle turn-off can influence yearly cattle prices, along with year to year market fluctuations (McCosker et al. 2010), real cattle prices have not increased dramatically over the last 50 years (ABOS 2005). Increases in Queensland's beef herds (ABOS 2008) and competition with more productive grazing lands south of the 16° parallel have influenced cattle prices and investment returns for Cape York Peninsula. For example on productive breeding properties south of the 16° line, regular pregnancy and foetal-age testing can identify and maintain cows in sync with seasonal feed cycles to produce one calf per 12 months, while selling or isolating unproductive cows producing calves out-of-season. Due to lack of pregnancy testing and less fertile soils on Cape York Peninsula, cow breeding frequency is extended to every two years, with impacts on profit, competition, and land degradation (Dr Ian Braithwaite, personal communication). Meanwhile, real costs for fuel and shipping have increased dramatically, despite easier access to markets on improved road systems on Cape York Peninsula.

Many grazing properties on Cape York Peninsula now have unsustainable levels of debt and negative farm cash income (e.g., McCosker et al. 2010; Gleeson et al. 2012). Some have been forced into financial receivership by the bank, continuing the vicious decadal cycles of property purchase, investment, bankruptcy, land degradation, abandonment, and resale of the most degraded, weed infested or poorly configured properties. On some properties severely degraded by weed invasion, the challenges of recovering pasture health for economic viability are often perceived to be in the 'too hard basket' for property investment into the future. On other properties, diversification of economic activity has become almost essential to stay in business, with many graziers having extra off-farm incomes and/or new enterprises on-farm. Some graziers are looking toward value added products from their leased properties, such as cattle fattening paddocks intensified with introduced fodder (e.g., *Leucaena spp.*), agriculture (e.g., bananas), or tourism development. Income from market-based conservation options has received less focus in the catchment.

The current economic situation for cattle properties in the Normanby catchment explains why there is little to no extra income (or time) to reinvest in long-term soil conservation actions. Preventing future gullies from initiating due to land use impacts makes local financial sense, as it can save money in the long-run. For example, the proper installation and maintenance of roads and fences can reduce gully erosion that threatens long-term access and functionality. Direct investments in intensive gully rehabilitation are less likely, as there is little immediate economic reason for investment. However, payments for ecosystem services (carbon, biodiversity, soil retention, weed and feral control) could change that situation, if they can pass the 'integrity' test by going beyond normal practice, be measurable and rigorously monitored, and be subject to peer review (Bray and Rolfe 2013). Currently, most of the costs of grazing impacts are externalised to the environment or public resources or cultural heritage. This is the case for real impact costs of erosion on nutrient loads, weed invasion, carbon emissions, biodiversity decline, river siltation, reef decline, cultural values at waterholes and across landscapes, etc.

The economic, social and cultural future of Cape York Peninsula is unknown and rapidly transforming. There are multiple competing and/or complementary development visions for Cape York Peninsula (e.g., Hill and Turton 2004; KBS 2007; Garnett et al. 2008) as well as new emerging ones. It is unclear how the continued grazing of cattle on highly marginal land with limited profitability – such as degraded terraces along river frontage with sodic soils and extensive gullying - will fit into one or more of these development visions. In most scenarios, alternative management strategies will be needed to address major gully erosion one way or another, unless these areas are truly deemed to be in the 'too hard basket' and left as wastelands.

8.2.2 Costs of Gully Rehabilitation

Implementing either direct/intensive or indirect/passive approaches to gully rehabilitation at the catchment scale to cumulatively reduce sediment yields will take considerable monetary investments from local, government, and/or market-based sources.

Despite both success and difficulties in stabilising alluvial gully slopes with intensive rehabilitation measures, the true challenge for this approach is the monetary cost of rehabilitation measures. The total cost (commercial retail) of intensive treatments conducted in this study ranged from $5000 to $6000 for 0.2 ha, which included heavy equipment hire and labour, gypsum, hydromulch, and fencing. Use of locally available compost and hand sown grass seed, rather than hydromulch, reduced this cost to ~ $3000 for 0.2 ha, but with slightly less effective results. Using local labour and machinery from individual properties could reduce costs further, along with government subsidies. Overall, it will cost $10,000 to $30,000 per hectare for intensive gully treatment. Results from this study indicate that this type of direct intervention can reduce erosion rates by 50 to 60% during the first year (CRGC1-40; CRGC1-29), and perhaps more during later years, but not stop or eliminate gully erosion altogether.

These costs are well above the average costs per hectare of grazing properties in the Normanby catchment (< $100 per ha). Costs per hectare of riparian frontage country for cattle grazing could be higher. Generally, there will not be a direct economic benefit to graziers to invest in direct/intensive gully rehabilitation for pasture production benefits. However, if key infrastructure is threatened - such as roads, fences, yards, buildings, dams, key waterholes - then the costs of intensive intervention might be worthwhile.

During the first round of the Australian Government Reef Rescue program (2008 to 2013), the average sediment erosion abatement cost paid by the government was $600/tonne for grazing land (Kevin Gale, personal communication). If this funding was allocated for intensive gully stabilization of CRGC1-29, then $3600 would have been available to reduce local erosion by 6 tonnes from > 11 t/yr to 5 t/yr, which would have been enough to cover costs (Section 7.13.5). If this funding was allocated for intensive gully stabilization of CRGC1-40, then $9600 would have been available to reduce local erosion by 16 tonnes from > 26 t/yr to < 10 t/yr (Section 7.13.4). At CRGC1-40, this project actually delivered > 16 tonnes of sediment abatement for $375 per tonne.

In the Normanby Catchment, Brooks et al. (2013) estimated that 736,400 tonnes per year eroded from alluvial gullies. If this input load was to be reduced by 10% or 73,600 t/yr, then at $375 per tonne of intensive treatment this would cost $27,600,000. Or alternatively, if 2000 ha of mapped gully in the catchment was treated with intensive intervention at $3000 per 0.2 ha, it would cost $30,000,000. Investing this level of government or market-based funding in the Normanby catchment might be better spent on purchasing large areas of degraded river frontage on specific cattle properties, and taking them out of cattle production as ‘soil conservation areas’ (Figure 14; Figure 18; Figure 152). However, this type of indirect rehabilitation action might or might not be as effective as intensive rehabilitation in the short-term, but would be in the long-term as landscapes and vegetation recover from disturbance (Section 7.5).

More detailed research and guidance is needed on the economic viability of gully erosion control measures, with and without government or market-based assistance for ecosystem services, and the profitability of marginal and remote grazing lands on Cape York Peninsula. For example, Yitbarek et al. (2012) studied the financial costs and benefits of gully rehabilitation by monetizing 1) loss of agricultural land area and productivity, 2) nutrient loss, retention and replacement costs, and 3) the overall rehabilitation expenditure. Future studies should additionally quantify the economic value of losses of sediment, riparian habitat and carbon sequestration potential along river frontages, as well as off-site impacts of downstream sedimentation, freshwater and marine habitat degradation, and cultural use of the landscape. The economic benefits of soil retention to grazing and farm production need more research. The economic and social costs of improving water quality by altering land use or potential conventional development pathways also need to be assessed in the Normanby (Binney 2010) and compared to culturally and environmentally appropriate economies envisioned for Cape York Peninsula (Hill and Turton 2004).

In light of these economic trade-offs, do the current Reef Rescue erosion control subsidies at small localised scales make sense compared to the profitability and scale of these marginal grazing lands degraded by gullying? Do these investments need to be scaled up and targeted at concentrated erosion hotspots (e.g., Figure 152)? Are there other economic alternatives to tackle these gully erosion problems under a different paradigm at a larger scale with resultant cumulative reductions in sediment yield? Can destocking river frontages degraded by gullies be traded and balanced with pasture and agriculture development on more productive soils that are less prone to erosion (e.g., basalt derived soils) and by following BMPs for nutrient retention (e.g., Figure 152)? What is clear is that the current paradigm of continuing to initiate and accelerate gully erosion and fixing one gully at a time with subsidies is unlikely to achieve long-term water quality outcomes and objectives to reduce sediment pollution (Howley et al. 2013).

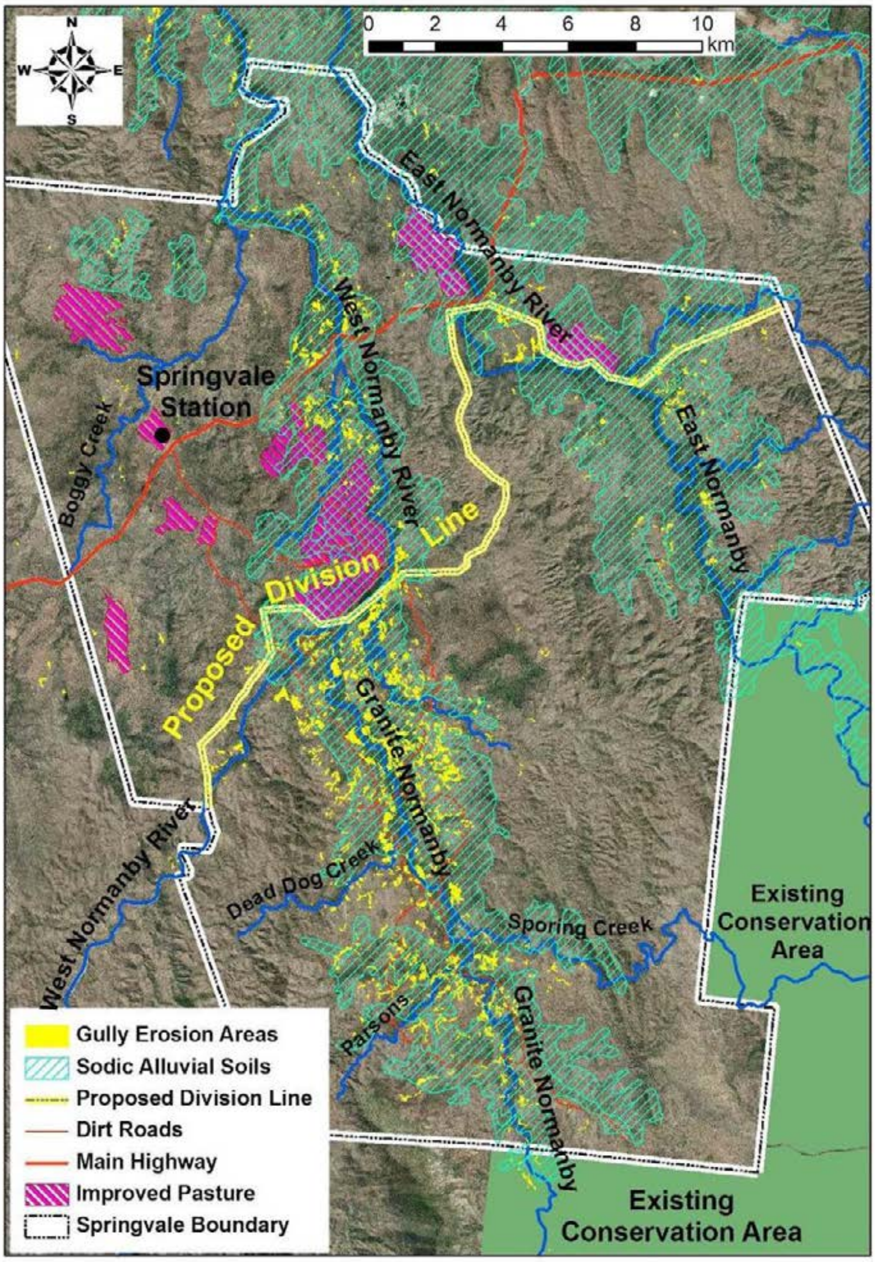


Figure 152 A DRAFT PROPOSED 'soil conservation area' - focused on the Granite Normanby River - where the highest concentration of alluvial gullies exists in the entire Normanby catchment. Note that existing 'improved paddocks' would stay under production and major monetary compensation would need to be provided to the lease holder for economic loss.

8.3 Political Challenges

8.3.1 Assessing Government Investments Using Modelling vs. Empirical Data

Current governmental programs such as Reef Rescue are not achieving water quality improvements at the catchment scale in the Normanby catchment. For every example of a positive project implementation outcome from a Reef Recue project in the Normanby there is an equal number that have failed to be implemented correctly or actually increased sediment erosion from project actions (Shellberg unpublished data). Accounting for project hectares 'improved' has been inflated and the significant impact of hectares of new development in the catchment has been ignored (new roads, agriculture, clearing, mining). The modelled assumption that the Reef Rescue program has reduced sediment loads by 1% (3000 tonnes) leaving the Normanby catchment by 2010 (Queensland State 2013) is totally unsubstantiated by empirical load data (Joo et al. 2012; Brooks et al. 2013) or field observations. Only improved empirical load estimates based on robust local field data can actually answer these questions (Joo et al. 2012; Brooks et al. 2013; Howley et al. 2013). Modelling approaches used for these estimates are fundamentally flawed, for example, by their over reliance on using remotely sensed surface vegetation cover and inappropriate erosion models on hillslopes to quantify changes in sediment and nutrient loads (Carroll et al. 2012). Local empirical data has shown that hillslopes are actually very low contributors to sediment loads in the Normanby, with most sediment coming from alluvial and colluvial gullies and bank erosion in small and large channels (Brooks et al. 2013). This is not to say that local grass vegetation cover does not influence these gully and bank sediment sources, which it does (Shellberg 2011; Shellberg et al. 2013a; this report). However, remote sensing techniques cannot measure grass ground cover accurately on woodland river terraces and frontage areas where water runoff reduction and soil cohesion are needed for erosion control. Furthermore, these concentrated hotspots on sodic soils to date have not been a focus for Reef Rescue funded projects. Actual field data and major rehabilitation projects are needed before these sediment reduction statements can be made or realised.

8.3.2 Government Policy and Investment in Large-Scale Erosion Reduction Projects

A fundamental paradigm shift in government policy is needed to refocus and increase government and/or market based investment into large concentrated areas of mapped gully and bank erosion in the Normanby catchment (i.e., sodic soils on river terraces), in order to actually reduce cumulative erosion and sediment yields at the catchment scale. For example, cattle grazing pressures need to be shifted away from large river frontage areas with dispersive or sodic soils prone to alluvial gully erosion. A holistic, long-term, process-based, catchment perspective is needed for erosion control, rather than the current Reef Rescue and Caring for Our County focus on small, discrete, short-term projects with questionable benefit that treat symptoms rather than causes (e.g., Robinsa and Kanowski 2011). Fixing one gully at a time with modest subsidies and cost-share will not achieve long term water quality outcomes at the catchment scale.

In these large gully erosion situations where reductions in grazing pressure in erosion sensitive areas will generate minimal private benefit but positive public benefit, then major positive (or negative) incentives are needed to promote environmental rehabilitation and sustainability. These incentives could include financial incentives via government investment or market-based solutions (carbon and biodiversity credits), or less desirable governmental regulation of severe environmental impacts. Alternatively, the costs of destocking river frontages degraded by gullies could be traded for government lease permission to invest in pasture and agriculture development on more productive soils that are less prone to erosion (e.g., basalt derived soils), as long as BMPs for nutrient retention were followed. Therefore, political support is needed to offer larger more targeted incentive packages to land and lease owners to invoke major changes in the land use paradigm at the property scale.

The use of both market-based or government payments for ecosystem services of combined carbon sequestration, biodiversity improvement, and soil conservation must pass the 'integrity' test (*sensu* Bray and Rolfe 2013). For example, actually sequestering carbon within soils on grazing lands in northern Queensland can be difficult even after major changes in management and perennial grass cover on degraded lands. To claim soil carbon credits, changes must be measurable, go beyond normal practice, be conservative, be rigorously monitored, be based on scientific peer review, be internationally consistent, and avoid future losses (carbon leakage)(Bray and Rolfe 2013). Thus, rigorous monitoring and adaptive management would need to be incorporated into these types of funding programs for soil, carbon, and biodiversity conservation.

Several lease owners in the Normanby catchment with concentrated areas of alluvial gully erosion have shown interest in possible government buy-back or market-investments to decommission from grazing large areas of degraded river frontage (>10,000 ha). Simultaneously, they are interested in pasture and agriculture development on more productive soils that are less prone to erosion, which could offset production losses on destocked degraded land. Ideally using these buy-back, market-investment, or land-use trade scenarios, large areas degraded by erosion could be transformed into significant 'soil conservation areas' that have multiple ecosystem service benefits. These benefits could include carbon sequestration, fire regime improvements, soil erosion reduction, terrestrial and aquatic biodiversity, river and reef water quality, water supply and weed control, as well as improving indigenous access and engagement to maintain cultural heritage and values. These 'soil conservation areas' in erosion prone areas could also be utilised as research stations to monitor large-scale, long-term experiments in savanna rangeland and gully erosion rehabilitation using different grazing and conservation regimes.

8.3.3 Extension, Training, Certification, and Soil Conservation Programs

It has long been argued that more extension officers with scientific and practical foundations are needed on the remote Cape York Peninsula to assist landowners with soil, water, pasture, weed and pest, and biodiversity conservation issues. Three to five (3-5) experienced field officers in disparate government and natural resource management (NRM) offices concentrated outside Cape York Peninsula are not enough to provide practical and sustained advice on the ground to local landowners. Ideally for soil conservation, a dedicated agency and local office such as the former Queensland Soil Conservation Service (SCS) is needed to assist and educate landowners. Additional capacity building could also occur through locally based Landcare officers who are respected by and live in communities (bottom up approach).

Expertise and funding are needed to help landowners on Cape York Peninsula with detailed and integrated property planning (stock/pasture/crop management, financial management, land management). Soil conservation plans at the property and catchment scale are integral to the land management plan. Once issues, plans and strategies are fully outlined on a property scale, then further funding and assistance is needed for action implementation and monitoring, such as addressing erosion hotspots using proactive grazing, fire, weed, and intensive rehabilitation measures.

Detailed training, design, implementation, maintenance, and monitoring assistance to land managers are needed for erosion and gully control actions and works at a variety of scales, to ensure that funded projects are effective in reducing erosion rather than actually accelerating it. Detailed interactions with landowners will also ensure that government funding is well targeted, not wasted, and accounted for.

The current Reef Rescue cost-share program is often locally seen as a ‘property development program’ for infrastructure where contracts are weak, actual and in-kind costs inflated, milestones breached, and actual soil conservation outcomes are not audited or enforced via contract. For example, some road and fence maintenance cost-share projects have been locally seen as a way to get ‘free’ diesel money to clear degraded roads and fences for immediate access and fire breaks. Often there is little regard to erosion sensitive areas or installation of frequent, large, functional water diversion structures (whoa boys), due to machine operator apathy or ignorance. In these situations, operators had not attended “grader workshops for erosion control” held locally in the catchment with Reef Rescue funding.

Machine-operator ‘certification’ programs for soil conservation projects should be used to ensure that machine use does not increase soil erosion through apathy or ignorance of best management practises on erodible soils. Both field and office training would be essential. This is especially needed for fence and road placement, design and maintenance. A prerequisite before government funding is provided to land owners, managers, and machine operators for erosion control should be the attendance at a detailed best management practice (BMP) course. Alternatively, direct implementation of erosion and gully control might be best conducted by a team of experts, practitioners and experienced machine operators, similar to historic project teams under the Queensland Soil Conservation Service (SCS).

While extension officers and soil conservation programs are needed for Cape York Peninsula, it could be argued that extension and outreach are most suited to landowners who will benefit privately or financially from knowledge transfer. Usually this is the case with intensive high-value operations that are losing productivity from sediment or nutrient loss and land degradation. For more marginal grazing enterprises with little to gain from reducing gully erosion, much larger positive incentives will be needed from government investment or market-based solutions as payments for ecosystem services (carbon, biodiversity, soil retention, weed and feral control). For the Normanby catchment and Cape York Peninsula, a mixture of approaches will be needed to cumulatively reduce erosion.

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10 Appendix

10.1 Pasture Monitoring Template

Site Name___________________________ Plot ID_____________________________
Date____________ Time____________ Plot Area (m^2)_______________________

GPS Tracklog Running? **Yes** ☐ **No** ☐
Photo of GPS Time Stamp? **Yes** ☐ **No** ☐
GPS Position Waypoint of Marker Stake? (*Time Averaged*) **Yes** ☐ **No** ☐

Plot Photos

Plot edge oriented North-South? (*Use compass*) **Yes** ☐ **No** ☐

2.5 m from Stake, Cantered on Stake, (North Looking South) Photo # _____________
2.5 m from Stake, Cantered on Stake, (South Looking North) Photo # _____________
6.0 m from Stake, Cantered on Stake, (North Looking South) Photo # _____________
6.0 m from Stake, Cantered on Stake, (South Looking North) Photo # _____________
Vertical Plot Photo (NE Quad) Photo # _____________
Vertical Plot Photo (NW Quad) Photo # _____________
Vertical Plot Photo (SW Quad) Photo # _____________
Vertical Plot Photo (SE Quad) Photo # _____________
Additional Site Area Photos (with Stake Ref.) Photo #s __________________________
Additional Plant Part Close-up Photos #s ______________________________________

Ground Cover (*aerial projection downward*)

Total % Organic Ground Cover____
(Nearest 5 %, standing grass/weeds, dead matted grass, roots, leaves, sticks, wood)
% of total = leaves/sticks________________
% of total = dead matted grass________________
% of total = standing vegetation (all)________________
% of total = standing weeds________________

Perennial Pasture Grass Cover (*rooted, standing, not herbaceous weeds*)___________
(Aerial Projection downward, not just basal area)
# of Species____________
Total Count (#) of Perennial Tussocks ______________________________
NE Quad_______, NW Quad_______, SW Quad_______, SE Quad_______
Species Names (if Known) ____

Pasture Yield Estimate (*kg/ha) (use plot area and immediate surroundings*)

Pasture Grass Yield (kg/ha)________________________________
(exotic or native grass w/out herbaceous weeds, shrubs, trees)
250 ☐, 300 ☐, 400 ☐, 500 ☐, 600 ☐, 800 ☐, 900 ☐,1100 ☐,
1300 ☐1600 ☐, 1700 ☐, 2000 ☐, 2200 ☐, 2400 ☐
Yield Guide Used (*Frontage, Yellow Earth, Granite*) ____________________________

Pasture Grass Yield (*with herbaceous or woody weeds kg/ha*) __________________
250 ☐, 300 ☐, 400 ☐, 500 ☐, 600 ☐, 800 ☐, 900 ☐,1100 ☐,
1300 ☐1600 ☐, 1700 ☐, 2000 ☐, 2200 ☐, 2400 ☐

Land Condition

Total % Organic Ground Cover (*see above*)________________________________

Perennial Pasture Grass Cover (*see above*)_________________________________

Dominant Pasture Plants (*list top 4 and total #*)_______________________________

____

Dominant Weed Plants (*list top 4 and total #*)________________________________

____

Weed Dominance *(% of individual plants*)
Abundant > 50% ☐, Mod 20-50% ☐, Low 5-20% ☐, Slight <5% ☐, None ☐

Soil Crust Condition (*broken-ness*)
Intact < 5% ☐, Slight 5-20% ☐, Moderate 21-50% ☐, Extensive >50% ☐

Erosion Features (*gullies, rills, tracks/pads, sheeting, scalds, hummocks, terracettes*)
Insignificant < 5% ☐, Slight 5-20% ☐, Moderate 21-50% ☐, Extensive >50% ☐

Deposited Material (*silt, sand, gravel, rock, not organic*)
Insignificant < 5% ☐, Slight 5-20% ☐, Moderate 21-50% ☐, Extensive >50% ☐

Vertical Distance from Stake Top to Soil Surface (*use tape measure*)
Upslope (mm)______________________
Downslope (mm)____________________

Overall Land Condition Class
A ☐ Good (*dense perennial grass, no signif. weeds, no signif. erosion*)
B ☐ Fair (*mod. perennial grass, a few weeds, minor erosion*)
C ☐ Poor (*low perennial grass, weeds common, obvious erosion/scalds*)
D ☐ Very Poor (*few perennial grass, weeds infestation, severe erosion/scalds*)

COMMENTS

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10.2 Monitoring Pasture Condition Instructions

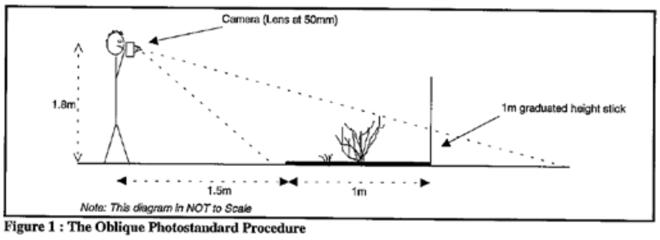
Goal = To monitor changes in ground vegetation cover, relative biomass, land condition, and cattle use before and after management change

A rapid appraisal method for pasture assessment (modified from Wilke 1997; Rolfe et al. 2004 and Karfs et al. 2009).

1. **Site selection**
    a. Use a random or systematic method to choose permanent reference points in a GIS or from field knowledge.
    b. Navigate to the chosen site using GPS coordinates.
    c. Adjust the exact location of the reference point by several metres if necessary to locate a representative and measureable monitoring point within the given geomorphic land unit and pasture type.
    d. Install a “star picket” as a permanent reference point at chosen site.
    e. Install a PVC sleeve around top of reference point for easy identification and labelling. Use metal tags if available.
    f. Collect a new GPS mark point to document the adjusted/chosen star picket location.

2. **Site Setup and Timing**
    a. Conduct assessment just before break in dry season (November) and also toward the end of the wet season (April).
    b. Assess land and pasture condition in a $4m^2$ (2m x 2m) area surrounding each star picket reference point at the centre point of the area.
    c. Use a PVC frame consisting of 4 lengths of 2m PVC to delineate the survey area for visual estimation and photo documentation.
    d. Orient one edge of the frame in the north-south direction using a compass so that the frame is consistently in the same position over time.

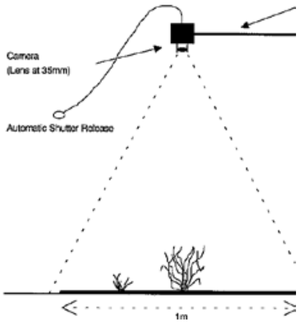
3. **Plot Photos**
    a. Record date, time, location, and GPS coordinates in notebook.
    b. Make sure GPS “tracklog” is running and take a photograph of the “time display” on the GPS to sync GPS and camera.
    c. Photo document pasture condition in a $4m^2$ (2m x 2m) area delineated with aluminium rods with star picket in centre.
    d. Use camera to take 4 standard oblique photographs of the plot area
        i. Walk ~ 2.5m due north from the star picket and face due south (use compass).
        ii. Aim camera down at oblique angle so that bottom edge of view is at the front edge of 2m x 2m sample area.
        iii. Note photo number in notebook.



Note: This diagram In NOT to Scale

Figure 1 : The Oblique Photostandard Procedure

    iv. Walk ~ 6.0m due north from the star picket and face due south. Take another wider-view oblique photograph toward the south. Include 5-10% of horizon in the photograph to gauge the area surrounding the plot. Note photo number in notebook.
    v. Repeat process of taking 2.5m and 6.0m photographs from the south looking due north.
e. Use camera to take 4 vertical photographs of the plot area, 1 of each quadrant (NE, NW, SE, SW).
    i. Stand on north or south side of the 2x2 m plot. Take a vertical photo looking down at the ground surface centred on the middle of each quadrant. Include both the edge of the plot frame and the centre star picket in each vertical photograph. Hold camera as high and far away from body as possible. Note photo numbers in notebook.



f. Use camera to take 1 photo looking vertically upward at tree canopy from centre of star picket. This will help estimate canopy cover. Note photo numbers in notebook.
g. When needed, take additional close-up photographs of plants needing identification or unusual weeds or circumstances.
    i. Use white paper or a black backdrop (plastic on cardboard) to improve photo quality and plant feature identification.
h. When needed, take additional oblique photographs of unusual circumstances around photo points.

4. **Ground Cover**
    a. Assess percent cover ratings of different types of ground cover.
    b. Using visual estimation sheets of percent cover:
        i. To the nearest 5% cover class (%5, 10, 15, 20, 25% etc.)
        ii. Consistently use the percent cover visual estimate diagrams (see attached) to guide estimates.
    c. First, assess the aerial cover (projected downward) of ALL ground cover in 2m x 2m plot.

        i. This is the proportion of the ground occupied by the aerial projection downward of all cover types including the standing aerial parts of plants/grass.
        ii. Include standing grass/herbs/weeds, live vegetation, leaves, sticks, dead grass, exposed roots, < 2m high.
        iii. Do not include cow dung.
    d. Second, assess the individual percentages of cover categories.
        i. For leaves/sticks and dead matted grass, it is difficult to ignore the percentage of leaves that "cover" other ground cover when using an aerial projection downward. Therefore use an oblique estimate of the percent cover over the ground occupied by leaves/sticks and dead matted grass.
        ii. For standing vegetation (all), standing weeds, and perennial pasture grass categories, continue to use the aerial projection downward method.
        iii. The standing weeds and perennial pasture grass categories should normally sum to equal % standing vegetation (all).
        iv. Include grader grass in the standing weeds category if it is attached and standing, or in the dead matted grass category if it is lying on the ground, matted and detached.
    e. Third, assess the perennial pasture grass cover, species, and total tussock counts.
        i. Include only perennial grass, but NOT annual grasses.
        ii. Include both native and exotic perennial grass.
        iii. Note number of species (types) and species names if known.
        iv. Count the number of tussocks of perennial plants (individual clumps) per quadrant by hand. Feel around by hand through the grass and cover to count tussocks. Focus on attached clumps and tussocks, but not annual grasses or herbs or weakly attached roots that are not perennial.

5. **Pasture Yield Estimation**
    a. Use photo standards to estimate standing dry biomass of grass and herb vegetation (not trees) in a 2m x 2m plot centred on the reference star picket.
    b. Use standards for "Frontage", "Yellow Earth", "Red Duplex", or "Range Soils" depending on location or condition.
    c. Estimate dry standing biomass of grass and herbs for an area of 4m^2 (2 m x 2m) surrounding a star picket reference point at the centre point.
    d. Do not assess tree saplings or surface litter cover
    e. First, estimate biomass for pasture grass yield ONLY. Include both exotic and native grass w/out herbaceous weeds, shrubs, trees.
    f. Second, estimate biomass with herbaceous weed cover in addition to standing pasture grass.
    g. Assess standing biomass to the nearest biomass class for a given soil land type.
    h. If pasture yield appears to fall between major categories, give it a rating half-way between by denoting, for example, 800/500 kg/ha.

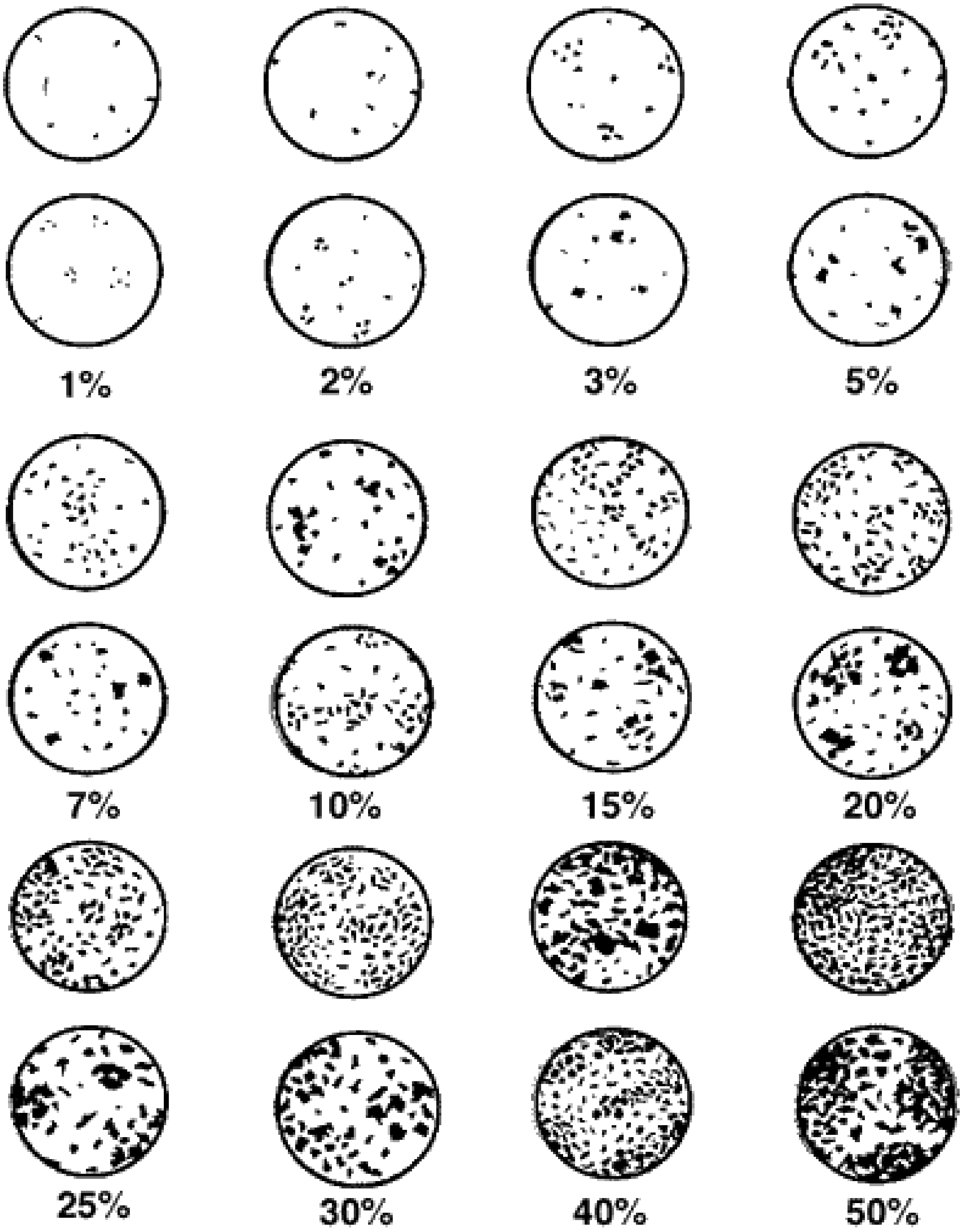
6. **Plant Species Identification**
    a. Take notes on known or speculative or unknown plant species in plot.
    b. Count different number (#) of species in plot.
    c. Take photos of different species when not known (use white or black background)
    d. In April during peak growth, collect plant parts (roots, shoots, flowers, seeds) and press in plant collection for later identification by the Queensland Herbarium.

7. **Land Condition Assessment**
    a. Use the ABCD condition classes to rate the condition of the plot area AND immediate surroundings.
    b. Use standards for “Frontage”, “Yellow Earth”, “Red Duplex”, or “Range Soils” depending on location or condition.

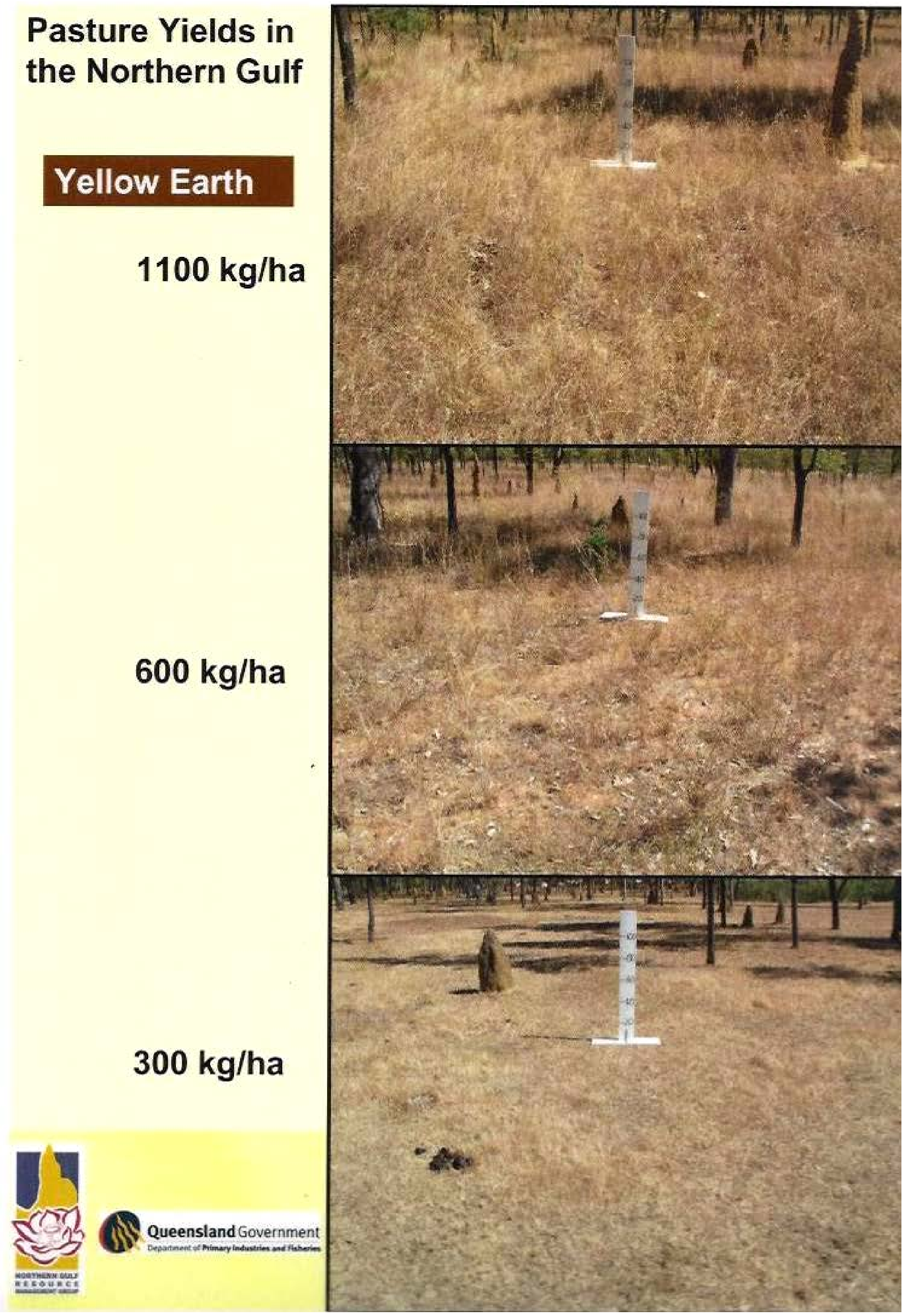
    c. Focus rating on existence of factors related to erosion.
        i. Perennial grass
        ii. Weed infestation (annual grass and perennial/annual weeds)
        iii. Soil condition or erosion (gullying, surface erosion, soil scalding, cattle tracks (pads), trampling).

    d. Use earlier ratings of percent litter cover and percent standing cover of grass/herbs to guide but not dictate overall rating.
        i. A = <30% bare ground, B = >30% but < 60%, C = >60%, D = severe erosion.

10.3 Guidance Sheet to Estimate Percent Cover



10.4 Visual Guides to Estimate Pasture Yield: Yellow Earth Example



Pasture Yields in the Northern Gulf

Yellow Earth

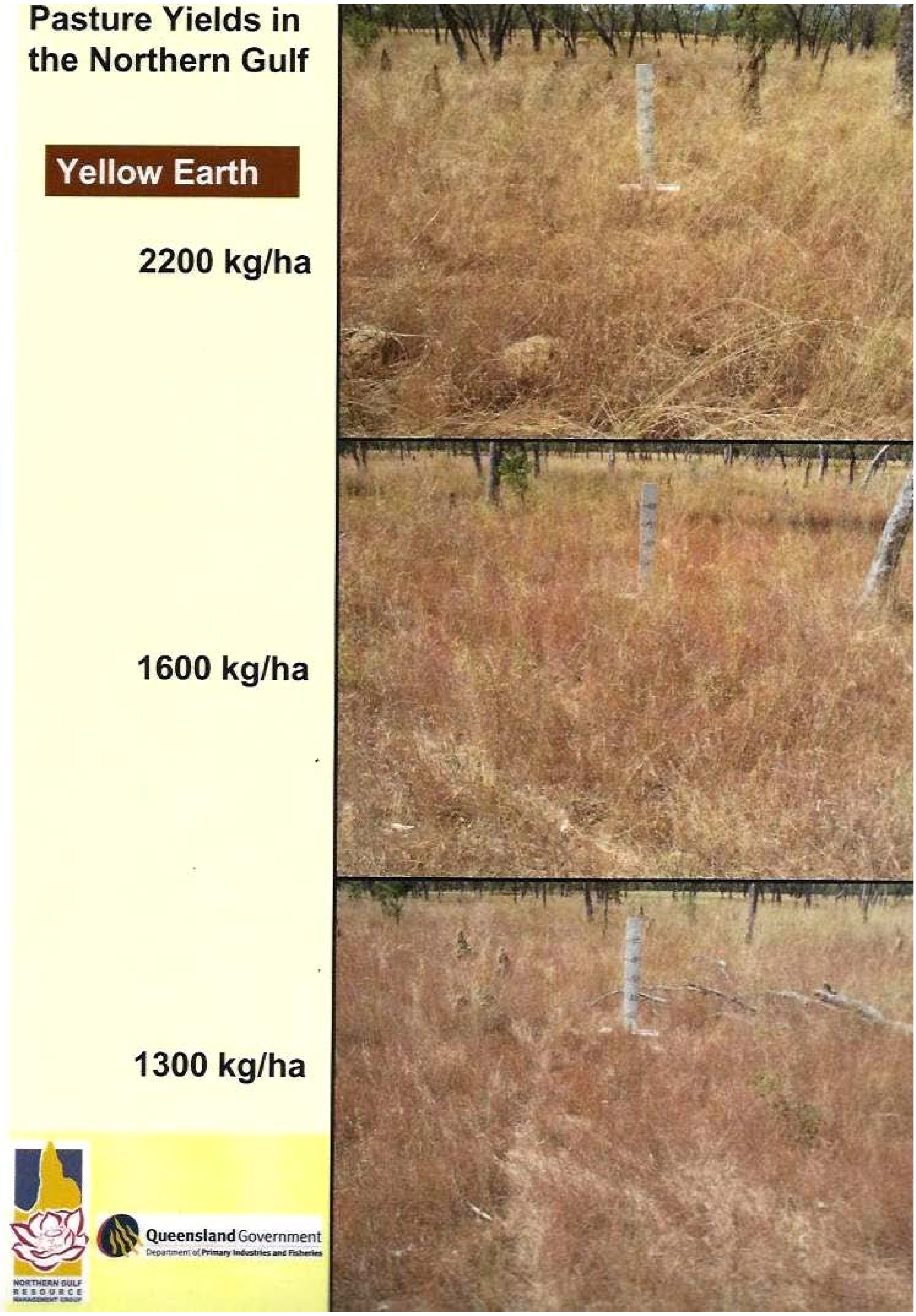
1100 kg/ha

600 kg/ha

300 kg/ha

Northern Gulf Resource Management Group

Queensland Government
Department of Primary Industries and Fisheries



Pasture Yields in the Northern Gulf

Yellow Earth

2200 kg/ha

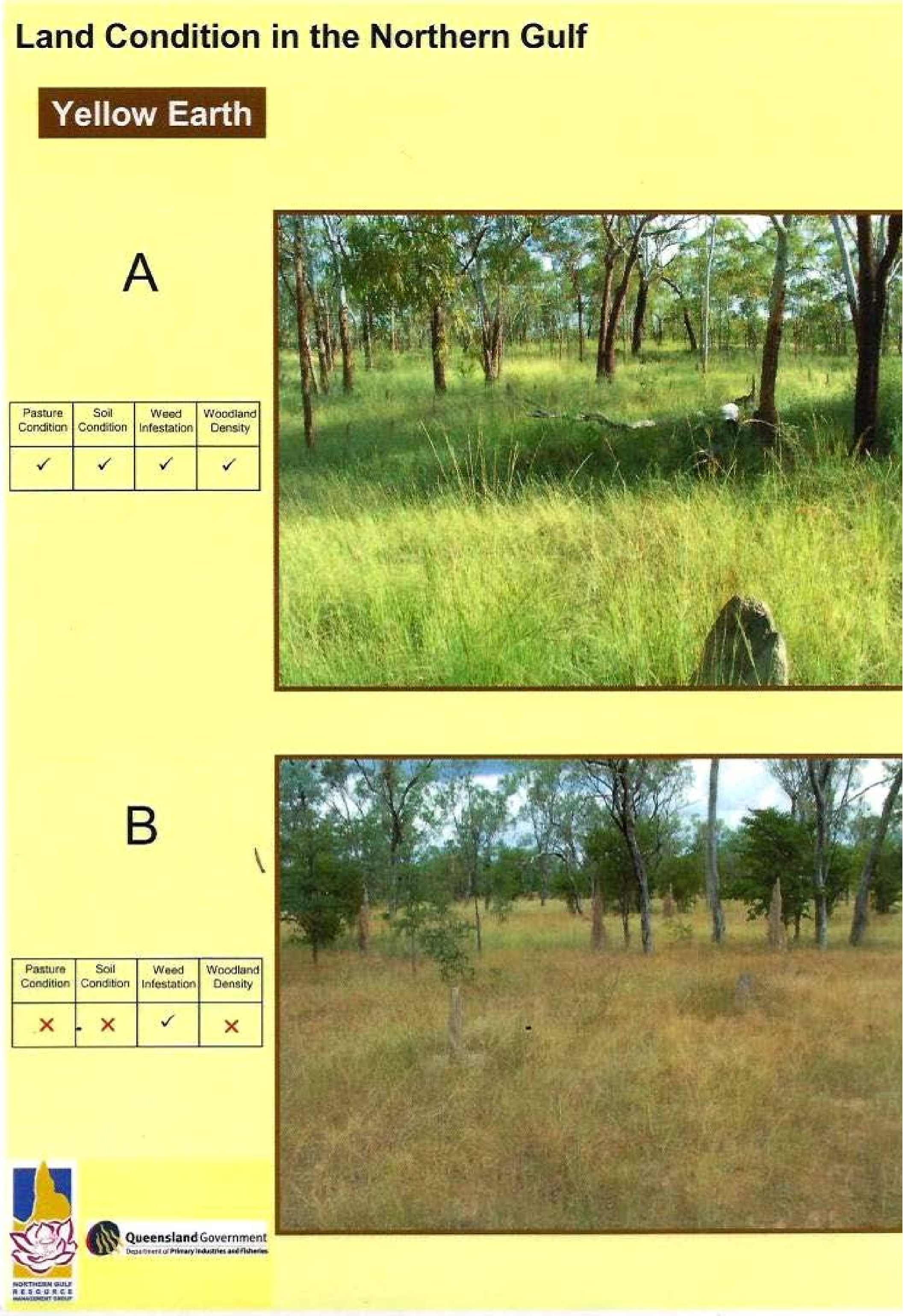
1600 kg/ha

1300 kg/ha

Northern Gulf Resource Management Group

Queensland Government
Department of Primary Industries and Fisheries

10.5 Visual Guides to Estimate Land Condition: Yellow Earth Example



Land Condition in the Northern Gulf

Yellow Earth

A

Pasture Condition	Soil Condition	Weed Infestation	Woodland Density
✓	✓	✓	✓

B

Pasture Condition	Soil Condition	Weed Infestation	Woodland Density
✗	✗	✓	✗

Northern Gulf Resource Management Group

Queensland Government
Department of Primary Industries and Fisheries

Land Condition in the Northern Gulf

Yellow Earth

C

Pasture Condition	Soil Condition	Weed Infestation	Woodland Density
✓	✗	✓	✗

D

Pasture Condition	Soil Condition	Weed Infestation	Woodland Density
✗	✗	✓	✗

NORTHERN GULF RESOURCE MANAGEMENT GROUP

Queensland Government
Department of Primary Industries and Fisheries

10.6 Grass and Plant Species Identified at Vegetation Monitoring Plots

Table 8 Grass and Plant Species by Plot Inside and Outside the Crocodile Exclosure (Old Hay Paddock: -15.710042°S; 144.679232°E)

Family	Genus	Species	Common Name	Comments	Plant ID	Plot Collected	Collected	Location Observed
POACEAE	*Aristida*	*hygrometrica*	Northern kerosene grass	Native annual grass	Grass 114	Plot 10	Crocodile	Crocodile
POACEAE	*Bothriochloa*	*pertusa*	Indian bluegrass, couch	Exotic perennial grass	Grass 01 Grass 105 Grass 121	511A, 515A	Crocodile	Crocodile
POACEAE	*Brachyachne*	*convergens*	Spider grass, Native couch	Native annual or perennial grass	Grass 113	Plot 9 upper	Crocodile	Crocodile
POACEAE	*Chloris*	*lobata?*	Chloris lobata	Native annual grass	Grass 132	Plot 5 lower	Crocodile	Crocodile
POACEAE	*Chloris*	*virgata*	Feather fingergrass, feather windmillgrass	Exotic annual grass	Grass 134	Plot 7 lower	Crocodile	Crocodile
POACEAE	*Dactyloctenium*	*aegyptium*	Egyptian crowfoot grass, Coast Finger Grass	Exotic annual grass	Grass 111	Plot 8 upper	Crocodile	Crocodile
POACEAE	*Dichanthium*	*sericeum*	Queensland bluegrass	Native perennial grass	Grass 017, 129	1040, Plot 2 lower	West Normanby, Crocodile	West Normanby, Crocodile
POACEAE	*Dimeria*	*ornithopoda*	Dimeria ornithopoda	Native annual grass	Grass 110	506A	Crocodile	Crocodile
POACEAE	*Ectrosia*	*nervilemma*	Ectrosia nervilemma	Native annual or perennial grass, Endemic to Cape York	Grass 103	507A	Crocodile	Crocodile
POACEAE	*Ectrosia*	*leporina*	Hare's-foot Grass	Native annual or perennial grass	Grass 126	525A	Crocodile	Crocodile
POACEAE	*Eleusine*	*indica*	Indian goosegrass, Wiregrass, Crowfootgrass)	Exotic annual grass	Grass 104, 116	507A, Plot 12 upper	West Normanby, Crocodile	West Normanby, Crocodile
POACEAE	*Eriachne*	*rara*	Wanderrie	Native perennial grass	Grass 102	507A	Crocodile	Crocodile
POACEAE	*Eriochloa*	*pseudoacrotricha*	Cup grass	Native perennial grass	Grass 118, 129	Plot 12 lower, Plot 2 upper	Crocodile	Crocodile
CYPERACEAE	*Fimbristylis*	*sp.*	Fimbry, fimbristyle, or fringe-rush	will investigate further	Grass 117	Plot 12 upper	Crocodile	Crocodile

CYPERACEAE	*Fimbristylis*	*sp.*	Fimbry, fimbristyle, or fringe-rush	will investigate further	Grass 124	505A	Crocodile	Crocodile
CYPERACEAE	*Fuirena*	*ciliaris*	Fuirena ciliaris	Native annual grass (sedge)	Grass 122	510A	Crocodile	Crocodile
POACEAE	*Heteropogon*	*contortus*	Black spear grass	Native perennial grass	Grass 003	1001	West Normanby	West Normanby, Crocodile
POACEAE	*Mnesithea*	*formosa*	Mnesithea Formosa	Native annual grass	Grass 112	Plot 8 upper	Crocodile	Crocodile
POACEAE	*Panicum*	*seminudum var.cairnsianum*	Panic	Native annual grass	Grass 008, 026, 101	1007, 1099, 507A	West Normanby, Crocodile	West Normanby, Crocodile
POACEAE	*Paspalidium*	*rarum*	Rare paspalidium	Native annual grass	Weed FFF	Plot 11 lower	Crocodile	Crocodile
POACEAE	*Perotis*	*rara*	Comet grass	Native annual to perennial grass	Grass 136	533A	Crocodile	Crocodile
POACEAE	*Rhynchospora*	*pterochaeta*	Rhynchospora pterochaeta	Native annual grass (sedge)	Grass 125	502A	Crocodile	Crocodile
POACEAE	*Sarga*	*Sarga*	Sorghum	Annual or perennial, exotic or native	Grass 127	525A	Crocodile	Crocodile
CYPERACEAE	*Scleria?*	*??*	Sedge	will investigate further	Grass 123	510A	Crocodile	Crocodile
POACEAE	*Sporobolus*	*coromandelianus*	Small dropseed	Exotic annual grass	Grass 119	Plot 11 lower	Crocodile	Crocodile
POACEAE	*Thaumastochloa*	*monilifera*	Thaumastochloa monilifera	Native annual grass	Grass 135	534A	Crocodile	Crocodile
POACEAE	*Themeda*	*quadrivalvis*	Grader grass	Exotic annual grass	Grass 002	1001	West Normanby	West Normanby, Crocodile
POACEAE	*Themeda*	*triandra*	Kangaroo grass	Native perennial grass	Grass 009, 013	1007, 1027	West Normanby	West Normanby, Crocodile
POACEAE	*Urochloa*	*mosambicensis*	Sabi grass	Exotic perennial grass	Grass 131? Grass 118? Grass 129?	Plot 3 upper	Crocodile	Crocodile
FABACEAE	*Aeschynomene*	*americana*	American jointvetch, Joint-vetch,	Exotic annual or short-lived perennial shrub	Weed CCC	Plot 11	Crocodile	Crocodile
AMARANTHACEAE	*Alternanthera*	*ficoidea*	Joyweed, Joseph's coat, Parrot leaf,	Exotic perennial herb/shrub	Weed K	1030	West Normanby	West Normanby, Crocodile
FABACEAE	*Alysicarpus*	*vaginalis*	Alyce clover, Buffalo clover, One-leaf clover,	Exotic annual or perennial herb	Weed EEE	Plot 12 lower	Crocodile	Crocodile

			Trebol Alicia					
FABACEAE	*Chamaecrista*	*rotundifolia*	Round-leafed cassia, Wynn cassia	Exotic short-lived perennial or annual herb	Weed II	1035	West Normanby	West Normanby, Crocodile
MALVACEAE	*Grewia*	*retusifolia*	Dogs nuts; Emu berry; Dysentery bush; Dysentery plant; Turkey bush; Emu-berries; Dog's balls	Native perennial shrub	Weed A, Weed B, Weed W	1001, 1080	West Normanby	West Normanby, Crocodile
LAMIACEAE	*Hyptis*	*suaveolens*	Mint weed, Horehound	Exotic annual herb	Weed D	1007	West Normanby	West Normanby, Crocodile
OROBANCHACEAE	*Rhamphicarpa*	*australiensis*	Rhamphicarpa australiensis	Native herb, Near threatened, Also collected on the East Normanby in 2001 by Jago, R.L.	Weed BBB	506A	Crocodile	Crocodile
MALVACEAE	*Sida*	*trichopoda*	Hairy sida, High sida	Exotic annual herb	Weed F	1020	West Normanby	West Normanby, Crocodile
RUBIACEAE	*Spermacoce*	*prob. latifolia*	Buttonweed	Exotic annual or perennial herb	Weed HHH	535A	Crocodile	Crocodile
FABACEAE	*Stylosanthes*	*humilis*	Townville stylo	Exotic annual herb	Weed DDD	Plot 12 upper	Crocodile	Crocodile
FABACEAE	*Stylosanthes*	*scabra*	Shrubby stylo	Exotic perennial shrub	Weed H, Weed AAA	1025, 507A	West Normanby, Crocodile	West Normanby, Crocodile

Table 9 Grass and Plant Species by Plot Inside and Outside the West Normanby Exclosure (Hwy Bridge: -15.762320°S, 144.976602°E)

Family	**Genus**	**Species**	**Common Name**	**Comments**	**Plant ID**	**Plot Collected**	**Collected**	**Location Observed**
POACEAE	*Alloteropsis*	*semialata*	Cockatoo grass	Native perennial grass	Grass 023B	1063	West Normanby	West Normanby
POACEAE	*Axonopus*	*compressus*	Blanket grass, Broadleaf carpet grass, Lawn grass	Exotic perennial grass	Grass 018	1046, 1118	West Normanby	West Normanby
POACEAE	*Bothriochloa*	*pertusa*	Indian bluegrass, couch	Exotic perennial grass	Grass 001	1001,	West Normanby	West Normanby
POACEAE	*Chloris*	*inflata*	Purpletop Rhodes grass	Exotic annual grass	Grass 022	1075	West Normanby	West Normanby
POACEAE	*Chrysopogon*	*fallax*	Golden beard grass	Native perennial grass	Grass 021	1078	West Normanby	West Normanby
CYPERACEAE	*Cyperus*	*sp.*	Sedge	will investigate further	Grass 010	1011	West Normanby	West Normanby
POACEAE	*Dichanthium*	*sericeum*	Queensland blue grass	Native perennial grass	Grass 017, 129	1040, Plot 2 lower	West Normanby, Crocodile	West Normanby, Crocodile
POACEAE	*Eleusine*	*indica*	Indian goosegrass, Wiregrass, Crowfootgrass)	Exotic annual grass	Grass 104, 116	507A, Plot 12 upper	West Normanby, Crocodile	West Normanby, Crocodile
POACEAE	*Eriachne*	*squarrosa*	Wanderrie	Native perennial grass	Grass 012	1015	West Normanby	West Normanby
POACEAE	*Eriachne*	*burkittii*	Wanderrie	Native annual or perennial grass	Grass 024	1060	West Normanby	West Normanby
CYPERACEAE	*Fimbristylis*	*sp.*	Fimbry, fimbristyle, or fringe-rush	will investigate further	Grass 007	1004	West Normanby	West Normanby
POACEAE	*Heteropogon*	*contortus*	Black spear Grass	Native perennial grass	Grass 003	1001	West Normanby	West Normanby, Crocodile
POACEAE	*Oplismenus*	*compositus*	Running mountain grass	Native perennial grass	Grass 027	1113	West Normanby	West Normanby
POACEAE	*Panicum*	*seminudum var.cairnsianum*	Panic	Native annual grass	Grass 008, 026, 101	1007, 1099, 507A	West Normanby,	West Normanby,

							Crocodile	Crocodile
POACEAE	*Panicum*	*trichoides*	Tropical panic grass	Native annual grass	Grass 028	1136	West Normanby	West Normanby
POACEAE	*Paspalidium*	*distans*	Spreading panic-grass	Native perennial grass	Grass 011	1011	West Normanby	West Normanby
POACEAE	*Paspalum*	*paniculatum*	Russell river grass	Exotic perennial grass	Grass 020	1084	West Normanby	West Normanby
POACEAE	*Rottboellia*	*cochinchinensis*	Itch grass	Exotic annual grass	Grass 016	1040	West Normanby	West Normanby
POACEAE	*Themeda*	*quadrivalvis*	Grader grass	Exotic annual grass	Grass 002	1001	West Normanby	West Normanby, Crocodile
POACEAE	*Themeda*	*triandra*	Kangaroo grass	Native perennial grass	Grass 009, 013	1007, 1027	West Normanby	West Normanby, Crocodile
POACEAE	*Themeda*	*arguens*	Christmas grass	Native annual grass	Grass 014	1027	West Normanby	West Normanby
PTERIDACEAE	*Adiantum*	*philippense*	Fern	Native perennial fern	Weed EE	1097	West Normanby	West Normanby
FABACEAE	*Aeschynomene*	*indica*	Budda pea, Jointvetches, Sensitive jointvetche	Native annual herb	Weed GG	1113	West Normanby	West Normanby
AMARANTHACEAE	*Alternanthera*	*ficoidea*	Joyweed, Joseph's coat, Parrot leaf,	Exotic perennial herb/shrub	Weed K	1030	West Normanby	West Normanby, Crocodile
EUPHORBIACEAE	*Antidesma*	*parvifolium*	Antidesma parvifolium	Native perennial shrub	Weed AA	1069	West Normanby	West Normanby
ASTERACEAE	*Bidens*	*pilosa*	Cobbler's pegs, Farmer's friend, Stick-tights, Pitch-forks, Burr marigold	Exotic annual herb	Weed CC	1095	West Normanby	West Normanby
ACANTHACEAE	*Brunoniella*	*acaulis*	Blue Yam	Native perennial herb	Weed FF	1097	West Normanby	West Normanby
FABACEAE	*Calopogonium*	*mucunoides*	Calopo, Wild ground nut	Exotic perennial herb	Weed HH	1120	West Normanby	West Normanby
VITACEAE	*Cayratia*	*maritima*	Coastal water vine	Native perennial vine	Weed J	1030	West Normanby	West Normanby
CAESALPINIACEAE	*Chamaecrista*	*absus*	Tropical sensitive pea	Native annual herb	Weed G	1023	West	West

							Normanby	Normanby
FABACEAE	*Chamaecrista*	*rotundifolia*	Round-leafed cassia, Wynn cassia	Exotic short-lived perennial or annual herb	Weed II	1035	West Normanby	West Normanby, Crocodile
EUPHORBIACEAE	*Chamaesyce*	*hirta*	Asthma plant	Exotic annual herb	Weed Z	1073	West Normanby	West Normanby
MALVACEAE	*Corchorus*	*sp.*	Jute	Native annual herb	Weed BB	1060	West Normanby	West Normanby
FABACEAE	*Crotalaria*	*medicaginea*	Trefoil rattlepod	Native annual or perennial herb	Weed DD	1095	West Normanby	West Normanby
FABACEAE	*Crotalaria*	*montana*	Fuzzy rattlepod, Woolly rattlepod	Native annual or perennial herb/shrub	Weed O	1089	West Normanby	West Normanby
ZINGIBERACEAE	*Curcuma*	*australasica*	Cape York lily; Native turmeric; Curcuma	Native perennial herb	Weed U	1081, 1084	West Normanby	West Normanby
DIOSCOREACEAE	*Dioscorea*	*bulbifera?*	Air potato, Round yam	Native perennial vine	Weed Q	1084	West Normanby	West Normanby
FABACEAE	*Galactia?*	*??*	Beach peas , Wild peas	will investigate further	Weed M	1035	West Normanby	West Normanby
MALVACEAE	*Grewia*	*retusifolia*	Dogs nuts; Emu berry; Dysentery bush;	Native perennial shrub	Weed A, Weed B, Weed W	1001, 1080	West Normanby	West Normanby, Crocodile
MALVACEAE	*Hibiscus*	*meraukensis*	Hibiscus	Native annual or perennial herb/shrub	Weed I	1025	West Normanby	West Normanby
LAMIACEAE	*Hyptis*	*suaveolens*	Mint weed, Horehound	Exotic annual herb	Weed D	1007	West Normanby	West Normanby, Crocodile
FABACEAE	*Indigofera*	*linnaei*	Birdsville indigo; Nine-leaved indigo	Native perennial herb/shrub	Weed C	1001	West Normanby	West Normanby
LYGODIACEAE	*Lygodium*	*japonicum*	Japanese climbing fern	Exotic perennial vine (fern)	Weed X	1080	West Normanby	West Normanby
CUCURBITACEAE	*Momordica*	*charantia*	Bitter Melon	Exotic annual or perennial vine	Weed LL	1147	West Normanby	West Normanby
PASSIFLORACEAE	*Passiflora*	*foetida*	Passion flower; Mossy passion flower; Love in a mist; Stinking passion flower; Wild passionfruit	Exotic perennial vine	Weed KK	1147	West Normanby	West Normanby

LAMIACEAE	*Plectranthus?*	*??*	Spurflowers	will investigate further	Weed N	1089	West Normanby	West Normanby
FABACEAE	*Rhynchosia*	*minima var. minima*	Rhynchosia	Native perennial herb or vine	Weed L	1033	West Normanby	West Normanby
ACANTHACEAE	*Rostellularia*	*adscendens sp. ?*	Pink tongues	Native annual or perennial herb/shrub	Weed V, Weed Y	1081, 1073	West Normanby	West Normanby
FABACEAE	*Senna*	*obtusifolia*	Sickelpod	Exotic annual herb	Weed JJ	1147	West Normanby	West Normanby
MALVACEAE	*Sida*	*trichopoda*	Hairy sida, High sida	Exotic annual herb	Weed F	1020	West Normanby	West Normanby, Crocodile
VERBENACEAE	*Stachytarpheta*	*spp.*	Snakeweed	Exotic perennial shrub	Weed ZZ	No plot, Abundant locally	West Normanby	West Normanby
FABACEAE	*Stylosanthes*	*scabra*	Shrubby stylo	Exotic perennial shrub	Weed H, Weed AAA	1025, 507A	West Normanby, Crocodile	West Normanby, Crocodile
TACCACEAE	*Tacca*	*leontopetaloides*	Arrowroot	Native perennial herb	Weed T	1084	West Normanby	West Normanby