Impacts of rehabilitating degraded lands on soil health, pastures, runoff, erosion, nutrient and sediment movement. Part II: Literature review of rehabilitation methods to improve water quality flowing from grazing lands onto the Great Barrier Reef.

RRRD.024 Final Report for the Australian Government's Caring for Our Country Reef Rescue Water Quality Research and Development Program

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CARING FOR OUR COUNTRY

Reef & Rainforest RESEARCH CENTRE

Rehabilitating degraded D-condition grazing lands: Literature Review

Project RRRD.024 Final Report Part II

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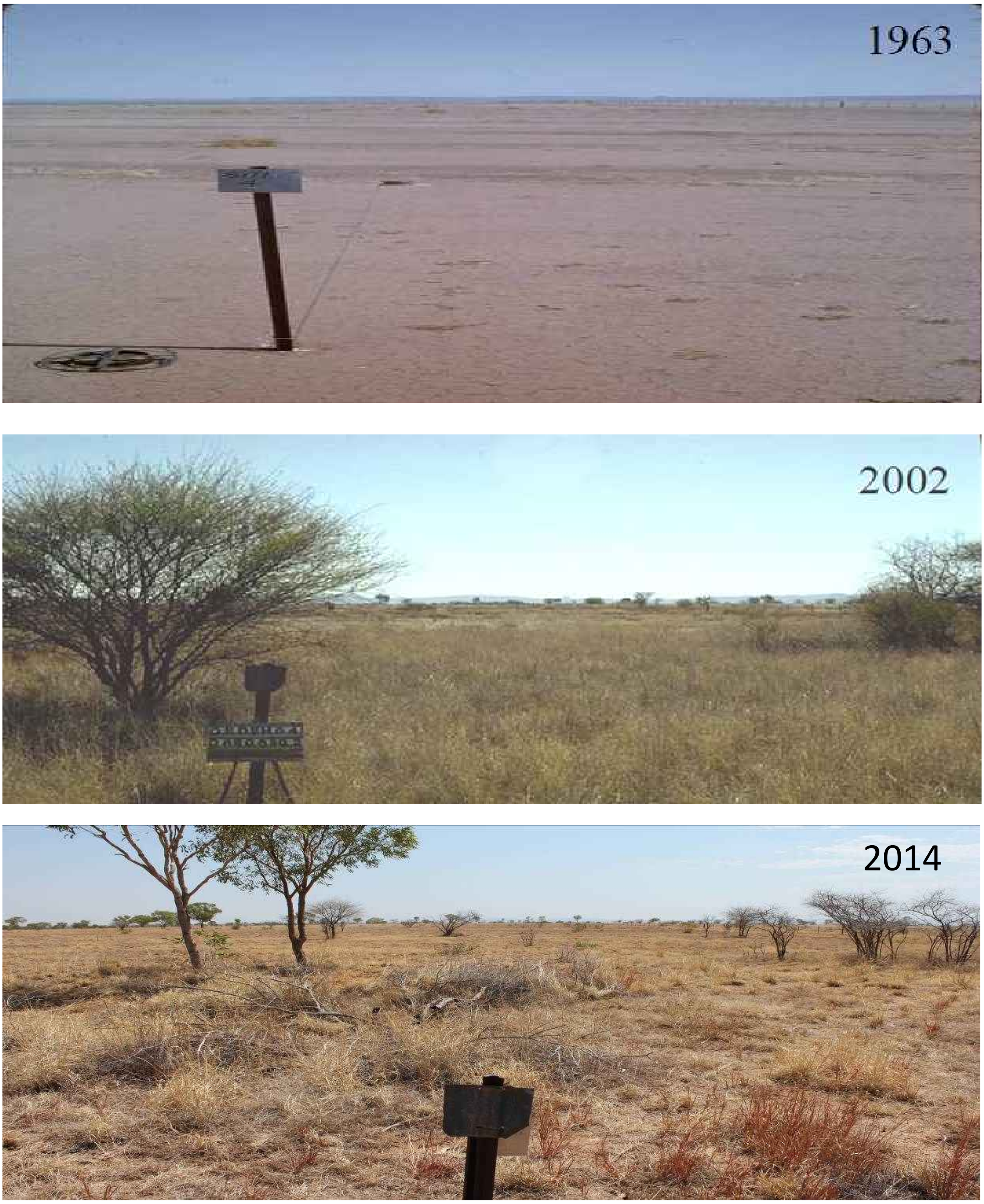

Ord River Regeneration Reserve monitoring site Ord H04 from 1963 to 2014.

This publication has been compiled by Richard G. Silcock and Trevor J. Hall of Queensland Department of Agriculture and Fisheries.

Summary

Over 200 potential references were reviewed with many covering aspects of water quality, grazing lands and their effects on the Great Barrier Reef (GBR), and rehabilitation of degraded landscapes. There was little reported information on the mechanical rehabilitation of bare, D-condition grazing lands in the reef catchments. There is, however, literature on machinery suitable for soil surface disturbance, pasture technology for developing permanent perennial pastures and on grazing management for improving C-condition land. This literature review is complementary to the other two aspects of this project, the field experiments of mechanical disturbance, and the landholder surveys on their rehabilitation experiences.

Rehabilitation of degraded grazing lands of the GBR catchments has become a major focus of the Reef Rescue Programme primarily because the large area of land involved has the potential to contribute significant sediments and nutrients to the GBR lagoon. Poor water quality from grazing lands has the capacity to do serious damage to the reef ecosystems. Any reduction in sediment runoff from eroding land implies a worthwhile improvement in water quality entering the GBR lagoon. A limitation with this idea is that it assumes almost no net losses as the turbid water moves downstream and minimal ability of the marine and reef ecosystems to recover from short-term stresses. Recent published research indicates that neither assumption is correct. It also does not recognise the dynamic nature of natural ecosystems in the semi-arid tropics where there is perpetual shifting of species dominance and mixes in response to the perturbations in the surrounding environment, particularly grazing pressures, climatic extremes and high seasonal variability.

High levels of sediment, pesticides, nutrients, or fresh water does kill or weaken some reef species, however, other species benefit, either directly by better using the incurring resources or by expanding into the ecological gap left by the damaged suite of species. For example, the increase in algae due to extra sediment and nutrients at the expense of hard corals is well known, but if the perturbation is short-lived (like a flood plume) or not widespread, then recolonisation by the displaced species can occur, provided no ongoing trauma occurs. However there is good evidence to suggest that the amount of sediment and nutrients reaching the ocean from agricultural and urban land is well above the 18th century levels, and thus could be damaging the reef ecosystems and the fishing and tourism industries that depend on them being in good health. There is also data to show that the quality of pastures on grazing lands is often poorer than 150 years ago and that areas of land may be denuded more than is desirable, particularly by grazing in drought periods.

Thus it is beneficial to all if better pasture quality and cover on grazing lands is encouraged and achieved. The main questions are what should the pasture quality target be and how can this be achieved at a realistic social and economic cost. Because the relationship between runoff and sediment load against ground cover is strongly non-linear, logic says that the greatest benefit will accrue from revegetating the barest areas, such as D-condition land. This eroded land is often found close to major watercourses so that the payoff is greater for the investment made in improvements because there is little scope for deposition of entrained sediment between those eroding areas and the nearby fast-flowing channel water.

Published studies, plus this project's research, have shown that the regeneration of healthy, perennial pastures on D-condition land is possible on many soil types provided several pre-

conditions and favourable seasonal co-incidences are met. These include: grazing animals, including macropods, have to be excluded completely for some time; significant disturbance of the soil surface is needed for all soils that do not have a natural loose surface; and, good growing season rainfall has to be received shortly after the surface disturbance and pasture seed has been sown.

If good rains are not received soon after rehabilitation, resowing of pasture seed may be needed along with re-cultivation to loosen and roughen the soil surface. There is a broad range of appropriate cultivation implements available for rehabilitation work, but the options for perennial grasses and legumes to sow are limited, as is the availability of adapted native species seed.

Cover pictures from Novelly and Watson (2004) and T J Hall (2014).

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Introduction

Rehabilitation Literature Review Objectives

The Great Barrier Reef (GBR) off the north-eastern coast of Australia is important to the National economy and is listed as a World Heritage Area. Maintaining its condition requires good water quality in the inner coastal lagoon. Research suggests there are risks to the reef from sediments and nutrients flowing from the land, including off grazing lands (Brodie *et al.* 2008; Brodie *et al.* 2009). McKergow *et al.* (2005) suggest the total suspended sediment supply to the GBR lagoon from grazing lands originates from the three forms of erosion; hillslope, gully and streambank. This review concentrates on the rehabilitation of degraded, bare grazing lands in D-condition that comes under the 'hillside' erosion definition.

The review outlines why rehabilitating D-condition grazing lands is a high priority in the overall Reef Rescue Programme, and reports on the history leading to the development of increased sedimentation. Improving water quality flowing off grazing lands into the GBR lagoon will have direct positive effects on the health of reef corals. The review includes published work that quantifies the impacts of rehabilitating degraded lands on soil health, pastures, water runoff, and nutrient and sediment movement.

The literature review is framed in terms of project objectives:

- The effects of different types of mechanical disturbance on infiltration rates and soil water storage; and on soil, water and nutrient losses;
- Time required for pasture recovery;
- Pasture production levels and hydrology after rehabilitation;
- How long the effects on hydrology last from a single disturbance;
- Costs and returns of rehabilitation in terms of both beef production and sediment reduction; and,
- Motivations and barriers to landholders rehabilitating degraded grazing lands.

Environment and drivers of threats to the Great Barrier Reef

We approached this review from the philosophical viewpoint that there was an historical level and pattern of landscape erosion on each land type and an historical pattern of stream discharge from rivers into the GBR lagoon between the coastline and the outer reefs (Figure 1). The Burdekin and Fitzroy River catchments are currently the largest and most significant contributors of terrestrial pollutants into the reef lagoon (Turner *et al.* 2013). By historical we envisaged events over the last few millennia but not on a geological timescale. These patterns were typified by great seasonal and year-to-year variation as recorded in the coral and sediment cores retrieved (Lough 2007) and by documented experiences since appreciable European settlement over 150 years ago.

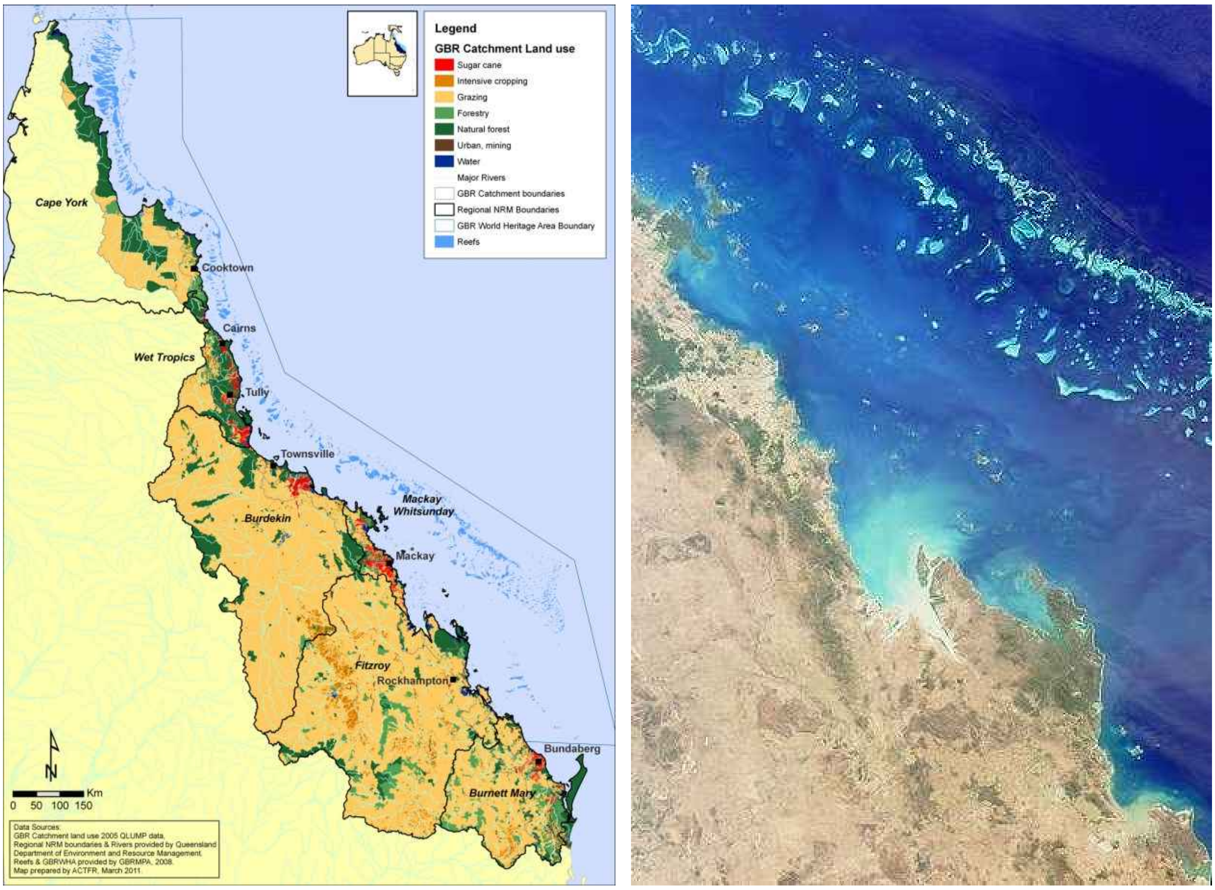


Figure 1. L. Great Barrier Reef catchments (Source: Brodie *et al.* 2012) and R. Reef lagoon Whitsunday region.

Early development of the landscape

In northern Queensland, gold was found around Charters Towers about 1870 and the Palmer River goldrush was in the mid-1870s, but before then ports such as Rockhampton (1856), Bowen (Port Denison 1861) and Townsville (1865) were staging places for early pastoralists and land speculators. It is likely that the first major increase in sediment and pollutant loads to the GBR lagoon came from the mining industry (Kennedy 1980). Much of today's near-stream gully erosion and unstable sediment sources may emanate still from the rubble and gullies created by such mining (Bartley *et al.* 2003; Streeton *et al.* 2013). The milky colour of the upper Herbert River is a relic from alluvial tin mining in the Mt Garnet region and old goldmines may be equally involved, and not from grazing activities (Fitzpatrick *et al.* 1995).

Figure 2. Tin mining: L. At Mt Poverty 1935 (courtesy John Oxley Library, Qld); and R. An example from Mt Garnet, Queensland 1990.

At present, the old gold mines do not leave a distinctive visual sign of their former extent, e.g. from satellite imagery. Bartley *et al.* (2003) remark for the Innot Hot Springs, Mt Garnet district "It was noted during the field reconnaissance that many of the gully systems were related either to mining, roads or power line installation. Gullies were not common in grazing lands that had good grass cover. However, the number and severity of gullies did seem to increase moving south-west from Innot Hot Springs through to Mt Garnet and the Gunnawarra Road area. This is most likely a function of the changing soil types and decrease in rainfall gradient along this section."

Hughes *et al.* (2009) have reported on changes in the source of sediments entering the GBR since European settlement from land use changes in one region of the Fitzroy catchment. These authors suggested a dominant source of sediments was from cultivation lands within areas subject to cropping, however, on a catchment scale they suggest erosion from channel sources is the largest contributor. Across this catchment the dominant landuse is grazing which can influence ground cover and water runoff into these channels. Good grazing management can maintain ground cover on hillsides and in channels reducing sediment loss into the GBR lagoon.

The significance of the old mining activities lies in their dependence on timber for pit-props and water for extracting the minerals from crushed ore. Thus many treatment works were in close proximity to streams and rivers where their tailings were and still are very readily mobilized by extreme flow events. Bartley *et al.* (2004) say that gully and streambank erosion contribute about 24% each to the fine sediment of the Herbert River mouth, compared to 52% from hillslope sources, but the mining areas mapped provide about 20 times the rate of sediment per unit area as native pastures, and 77 times that of improved pastures. Forests and 'other reserves' contribute at twice the rate of native pastures which is explained as being due to the steeper slopes, higher rainfall and the inherently more erodible nature of the soils there. Old abandoned mines and ore treatment plants, now overgrown with vegetation, are more extensively spread amongst all land types than has been mapped and they can be major contributors to sediment from many land types (Bartley *et al.* 2003). No reports were found on any erosion studies on grazing land under contrasting stock management in the Cape York region, however, Shellberg and Brooks (2013) have reported on alluvial gully erosion and suggestions for management of this form of erosion for the Normanby catchment of the Peninsula.

The early impact of feral pigs in Queensland forests and wet lands (McGaw and Mitchell 1998) may be a source of sediments since early European settlement (Figure 3). Pigs thrived in riparian environments and that probably also suited the human inhabitants who used them as a source of meat (Roberts *et al.* 2001).

Figure 3. Typical wild pig mob foraging near water.

Introductions to the environment

Preserving GBR ecosystems is not addressing a static target or set of targets but about assigning relative priorities to outcomes based on the value and costs associated with defining and achieving targets (Bui *et al.* 2011). New organic and inorganic materials have been introduced to the environments that affect the reef ecosystems since European settlement. No ecosystem was ever static and the characteristics and bounds which humans assign to them for convenience, e.g. Regional Ecosystems (Sattler and Williams 1999) are constructs that can never be fully circumscribed and never modelled with a high degree of accuracy. The GBR, its islands and the coastal lands on its western fringe that were in a semi-stable relationship with each other, with slow inevitable drift in location, ecosystem makeup, species diversity and abundance in response to natural forces, are now under greater pressure to modify and adapt to the new reality.

What is endangered in the GBR?

The GBR has a range of coral reef types (Wilkinson and Brodie 2011) that have evolved in a range of environments that relate to their nearness to the main shoreline, influenced by fresh water and sediments, and affected by the underlying geology, ocean current patterns, and their proximity to major river mouths (Figure 4). The structure and growth pattern of each reef can be described in general terms (van Woesik *et al.* 1999). The literature suggests that average salinity and turbidity of the enveloping waters determines what suite of corals and other life forms inhabit each ecosystem (Lough and Barnes 2000). Some organisms are very slow-growing, sedentary and long lived, such as brain corals, while others are fast growing, mobile and have short lives, such as shrimps, algae, diatoms and some insects. Other animals are migratory and inhabit the region intermittently, such as turtles, whales and birds.

Figure 4. Contrasting coral health: L. Dull unhealthy; and R. Bright coloured, healthy coral.

The impact of management practices on grazing land hundreds of kilometers inland from the coast impacts on GBR life in an indirect way. One obvious way that the extensive grazing lands of north Qld interact with the GBR ecosystems is via the water that flows from hillsides to creeks to rivers draining those grazing lands. A less obvious way might be via any change in the atmosphere that grazing land use might cause which then affects life in the ocean around the GBR, such as temperature or rainfall change. Coral bleaching has been documented and has been attributed to increased water temperatures (Wilkinson 2000), but we find no reliable evidence that such increased air temperatures are directly linked to grazing land use in Queensland.

We also have found no evidence that coral bleaching is a permanent effect that prevents recolonisation of an area by the same or similar corals within a few years (Marshall and Schuttenberg 2006). Coral bleaching has been linked to the 'El Niño' climate phenomenon which has major effects on Queensland's reduced rainfall and increased temperature extremes (Partridge 1994; McKeon *et al.* 2004). There is no evidence that grazing land management influences the cyclical onset and decline of these El Niño events. Ground cover is reduced in these El Niño years due to grazing and lack of pasture growth from the drought years, which potentially allows increased water runoff carrying higher sediment and nutrient loads.

Figure 5. The idealized, tourist view of what healthy coral reefs should all look like.

We find no strong evidence that changed rainfall patterns alter coral ecosystems or that rainfall directly changes coral ecosystems markedly (Figure 5). There is ecologically sound data that shows that some corals do not survive where influxes of freshwater are regular (Marcus and Thorhaug 1981), but that is why there are different reef types close to the main shoreline compared to those well offshore (Hutchings *et al.* 2005). The El Niño effect does influence the rainfall received over the GBR Lagoon and the hinterland and seems also linked to the frequency with which tropical cyclones cross the Queensland coast. Such cyclonic events damage coastal forests and dump huge amounts of rain which inevitably cause heightened erosion and huge river flows which are loaded up with far greater quantities of sediment than normal. That sediment is a common cause for concern (Rogers 1990) for reef health and grazing lands do contribute to the sediment load in the rivers and will be discussed in detail later. However, the management of grazing lands is not driving the El Niño rainfall but can significantly influence the impact that such rainfall has on the sediments, nutrients and pesticides entrained in the floodwaters that head towards the GBR lagoon.

Sowing improved grass and legume pastures for cattle grazing in the reef catchments can increase ground cover, but it can also cause an increase in grazing pressure on the land. Legume based pastures such as leucaena (*Leucaena leucocephala*) and butterfly pea (*Clitoria ternatea*) can also increase the potential for higher nitrogen and phosphorus losses, compared with grass only pastures (Thornton and Elledge 2013). These nutrient losses remain lower than potential losses from cropping the same soil types. Such legume pastures are established on the more fertile soils that usually are not degraded. Over-grazing these soils, especially areas close to watercourses, will increase the supply of sediments and nutrients to rivers flowing into the GBR.

Rehabilitation aspects reviewed

Effects of different types of disturbance

Degraded, D-condition, country can be the result of different forms of erosion damage. It can be primarily gully erosion where there is still a source of seed of local species available to provide regenerative vegetation (Figure 6), or it could be largely from sheet erosion where the topsoil and seed of adapted local plants has largely been lost (Figure 7). Different mechanical strategies are required to fix these differing problems. For example, waterponding can be effective on flat landscapes but is not considered for deep gullied land. Streeton *et al.* (2013) recommend a review of the geomorphology of the degraded area, the soils and vegetation, as well as land management options is required before any rehabilitation is commenced.

Figure 6. Gully erosion in the Ord River area 1960's.

Figure 7. Kimberley WA: L. Sheet erosion in 1960s from Payne *et al.* (2004) and R. Degraded grazing country 2014.

It is understood that rehabilitating badly scalded country requires a change to the nature or roughness of the soil surface to increase water infiltration. Even waterponding works by altering the chemistry of the soil (Sullivan 1992a) so that it ceases to slake down and develops cracks in the surface and down through the profile. Disturbance of the soil surface gives pasture a chance to re-establish in several ways. It enables seeds to be trapped (if blowing in from adjacent pastures) or retained (if deliberately sown) on the site until rain falls to germinate the seed. It also holds rainfall in the surface depressions and channels created by a cultivator so that it has more time to infiltrate into a slowly permeable soil and so that it cannot rapidly runoff (Lang 1979; Webb 2003).

Badly scalded or eroded surfaces with exposed subsoil are often sodic and do not retain a crumb structure when wet, and particularly when raindrops fall causing surface sealing (Rengasamy and Olsson 1991). Such slaking cannot be completely prevented but larger soil clods take longer to 'melt' down and deeper pits, trenches or holes in the surface take longer to fill up with silt. Deeper pits also hold more water which should penetrate deeper into the soil profile and hold water for longer for plant seeds to germinate. Hence disturbance recommendations are to create as rough soil surface conditions as possible. The choice of disturbance implement and the depth of ploughing is often a compromise between degree of surface roughness achievable and the cost of ploughing or ripping to a greater depth.

Mechanical disturbance machinery

Sullivan and Kraatz (2001) provide a review of the various mechanical disturbance implements and of the soil types they are suitable for rehabilitating. A range of tyne and disc implements may be used, but a rotary hoe type is not recommended. They pulverize the soil, breaking sown any structure, create a fine dust, and leave the soil susceptible to wind erosion. After rain the fine soil particles can slake down to a smooth, scalded surface again.

Heavy-duty rippers (Figure 8) are often recommended rather than traditional cultivation with disc, tyne or mould-board plough. Rippers are mounted on a high-horsepower tractor with positive downward pressure applied to force the tynes deep into the hard soil.

Figure 8. Deep ripper on a three-point linkage.

The most adaptable cultivator is a tyned plough (chisel plough) that leaves the surface rough and can penetrate to the required depth of at least 25 cm on some soils. The number of tynes on the toolbars depends on the pulling power of the tractor. There are trailed and 3-point linkage mounted types of chisel ploughs (Figure 9). They may require extra weight on the toolbar to get sufficient depth penetration. Small wings behind the points improve the breakup of tight soils, while narrow points do not break up tight soil sufficiently. The Yeoman's type tyned plough has been successful in penetrating and breaking up hard soils for pasture rehabilitation.

Where there is easy access for ground machinery, more sophisticated equipment can be used such as air-seeders and press wheels that allow greater accuracy of seed placement and distribution.

Figure 9. Chisel ploughs: L. Trailed hydraulic type; and R. A 3-point linkage mounted type.

The crocodile plough seeder (Figure 10) does not make deep enough pits in hard-setting, scalded soil surfaces and has limited use for mechanical disturbance in rehabilitating these sites. It is more suited for pasture seed distribution of multiple seed lines at the same time and for oversowing into softer country that is not as badly degraded. It has the advantage of getting over logs and small woody plants and using less power to pull per metre of width, so is less costly to operate than cultivating implements.

Figure 10. L. Crocodile plough seeder ex. hoopersengineering.com; R. Single cylinder crocodile plough seeder (Fitzroy River WA regeneration)

Offset discs (Figure 11) are suited to the more friable, heavier textured soils, because they don't penetrate deeply enough into a dense/hard soil. Scalloped discs (Figure 12) are similar but they penetrate hard soil surfaces better and roll over obstacles (Bakker 1999, page 321). However, neither of these implements is recommended by Sullivan and Kraatz (2001) because they produce a fine tilth that slakes down readily and can reform crusts.

Figure 11. Offset disc plough ex. http://reveg-catalog.tamu.edu/index.htm

Figure 12. Scalloped offset discs ex. gumtree.com.au

A twin off-set disc machine with deep rippers breaking the crust and a roller drum seeder (Figure 13) has been used widely in the Ord and Fitzroy River regeneration programs (Sullivan and Kraatz 2001; Fletcher 2013).

Figure 13.Twin off-set discs with deep ripping tynes and roller seeder for shallow ponding bank regeneration of scalds (machines used in the Ord and Fitzroy River regeneration programs in WA).

Mould-board ploughs (Figure 14) are not recommended because they invert the soil and can bring sodic or saline subsoil up to the surface (GRDC 2010), and also the straight channels formed can develop into deep rills or small gullies during intense storms.

Figure 14. Mould-board plough (ex Wiki images).

Removal of grazing animals is essential

No literature was found that rehabilitation of severely degraded, eroded land can be achieved in the continued presence of any large herbivores. Experience in the VRD and the Ord River catchment shows that removal of all livestock is essential for some years (Fitzgerald 1976; Hacker 1989; Novelly and Watson 2004). There may be a need to cull native macropods as well (ABC 2012) because they can increase to excessive densities in the absence of competitors and with the abundant forage that has grown during the rehabilitation process.

Once animals are removed, regeneration of some types of country can be rapid, if seed is present and seasons are good (Novelly and Watson 2004; NRandW 2006a). However, several growing seasons without stock is usually required and thereafter grazing management must be very astute to ensure that the newly established pastures persist (Ryan 1981).

The rate of recovery is inversely proportional to the extent of topsoil loss. If losses have been small, there is still adequate soil fertility and water holding capacity to allow a pasture to grow that is nearly as resilient as the original pasture. Also there may be a natural seed reserve in the soil from which regeneration can occur without the need to resow (Fitzgerald 1968a; Ryan 1981). The new pasture then begins to stabilize the erosive features of the country by trapping locally mobilized sediment and stabilizing rills and gullies that are not too far advanced (Streeton *et al.* 2013).

In an old continent like Australia, there are many soils that have shallow topsoil and a subsoil that is inhospitable to plant establishment and growth. Some are amongst Sodosols, Chromosols and Kurosols (Isbell's Australian classification system). They have drawbacks that hinder rapid rehabilitation. Firstly the friable, fertile topsoil layer is shallow, often less than 15 cm and thus easily lost completely under severe erosion. Secondly the subsoil has poor water and root permeability, often high concentrations of salts, a poor sodium/calcium ratio that makes them set hard when dry, become extremely boggy when saturated with moisture and highly erodible because they lack coherence between soil peds. Once this type of sub-soil is exposed at the surface of the land, rehabilitation becomes an extremely difficult, requiring severe mechanical intervention and very long-term task that is expensive and never guaranteed of success. The common term used for these soils is 'sodic soils' (Sumner 1995) and the worst types are soils of sandy loam to sandy clay texture with a non-cracking clay type (Sumner 1995). The sodicity makes them erodible and difficult to cultivate and in some cases salinity further reduces the availability of soil water to plants and is toxic to sensitive species.

How to exclude grazers

Fencing degraded country and including any adjacent areas that provide excessive runoff to the damaged area is the first approach. Electric fencing technology has shown that a 'hot' wire is insufficient to prevent a determined animal and is no barrier to marsupials. There is research on ways to deter animals from entering an area or crossing an electronic barrier (Umstatter 2011). The deterrent factor has to be operating continuously over the whole area where stock exclusion is required. Controlling or eliminating water sources is another option.

Experience has shown that heavy clay soils that become boggy in wet weather act as a natural deterrent to stock ingress (WA Rangeland Management Branch 2003) and that this has assisted in maintaining reasonable condition of pastures on these soils over many years in northern Australia. It has however, caused a big increase in the grazing pressure then exerted on the remaining country that is less boggy at that time but in need of reduced grazing pressure afterwards to allow crown regeneration and seedling recruitment.

Exclusion of native and feral animals, especially kangaroos and wallabies, can be a difficult problem. The large macropods (red and grey kangaroo and euros) consume a lot of grass in their diet (Dawson and Ellis 1979). Many of the larger wallabies also consume a large proportion of grass, e.g. the agile wallaby (*Macropus agilis*) and so threaten resowing efforts that are mostly seeking to re-establish a grass-dominant pasture (Fitzgerald 1976; Novelly and Watson 2004).

In many areas that drain into the GBR lagoon, feral pigs can cause serious pasture disturbance and an erosion susceptibility problem, especially in riparian areas that may be reduced to D-condition by prior land use. Pigs feed on the crowns and roots of succulent plants and can destroy many hectares of pasture in their search for tubers and fleshy rhizomes, such as are found on goldenbeard grass (*Chrysopogon fallax*), cockatoo grass (*Alloteropsis semialata*) and Mitchell grass (*Astrebla* spp.). They also seek shelter in long grass and shady places that would be more likely to exist in a protected, ungrazed area than in surrounding grazed country. Restricting pigs with fencing is difficult but a concerted shooting, trapping or poisoning programme can be effective (DAFF 2013).

Benefits to the environment can be achieved by getting the cover back on the land and thus the rate of sediment entrainment reduced. The environment does not pay the business directly in cash, only via improved production or increased asset value over a long time frame, yet the business and its external backers (Government or the community) have to provide the money and resources for the fencing in advance of any water quality improvement. Classic economic analyses that use acceptable discount rates to value future returns rarely suggest value-for-money compared to alternative investments that have a short payback period, such as housing, mining and tourism (Quiggin 1997).

Incentives for rehabilitating D-condition land

Various public and scientific sources are calling for a reduction in the pollutants that are reaching the GBR lagoon (GBRMPA 2001; Fabricius 2005; Bligh 2008). Action has been implemented (BRREP 2013; FutureBeef 2013) and changes are occurring (FBA 2008; Brodie *et al.* 2012), however, producers are still looking for well-targeted information on how to reduce off-farm losses with a high degree of success (Webb 2003). The literature indicates that extensive grazing industries are regarded as having their greatest impact via sediment loads that reach the reef lagoon (Roth *et al.* 2003; Devlin and Brodie 2005; Bartley *et al.* 2009; Waterhouse *et al.* 2012; Weber *et al.* 2012) and that local erosion material (Figure 15) moves into river courses where they can be intermittently remobilized during future big runoff events (Post *et al.* 2006, Wilson *et al.* 2008b).

Chemicals and herbicides are a minor potential threat with tebuthiuron and hexazinone being most commonly detected and at very low levels and only close to the coast (McMahon *et al.* 2005; Lewis *et al.* 2009). In the 2010-2011 wet season of all major coastal rivers flowing into the GBR, the Fitzroy River outflow produced the largest annual load of atrazine (approximately 2400 kilograms) and also the largest load of tebuthiuron (approximately 6000 kilograms) (Turner 2013). Tebuthiuron (sold as Graslan^{R}) is widely used by the grazing industry for tree management in this catchment. Fertiliser use has also been blamed especially inorganic nitrogen (Mitchell *et al.* 2009; Waterhouse *et al.* 2012), but much of that comes from sugarcane lands that are close to the coast. The largest quantities of the nutrients, nitrogen and phosphorus, in runoff into the GBR come from the two largest catchments, Burdekin and Fitzroy; however, they both have very low yield rates because of their dominant land use, cattle grazing on unfertilised grass pastures (Turner *et al.* 2013).

Figure 15. Photo of scalded riparian area with reasonable cover further away.

Sediments from grazing lands come from sheet (otherwise called hillside) erosion (Figure 16) and/or gully erosion. Degraded land is often in close proximity to watercourses because the degradation from overgrazing is exacerbated by the regular movement of stock into and way from permanent water sources in those rivers (Fitzgerald 1967; Roth *et al.* 2003; FBA 2006b, c). Cattle pads act as waterways for runoff and, if erosion is severe enough, it cuts into the subsoil and many Queensland soils have highly dispersible sodic subsoils (Bui *et al.* 1995) that flocculate and are then carried great distances in floodwaters. Being primarily of clay mineralogy they are relatively nutrient rich, especially in P, and pass through dams and most other riverine obstacles all the way to the sea (Roth *et al.* 2003, McKergow *et al.* 2005). Subsoil erosion also undercuts the still stable surface layers and results in mass collapse of gully walls (Catchments and Creeks 2010) to greatly increase the amount of instream sediment available for transport downstream. In soils of alluvial origin, common along major tropical rivers, there is no bedrock near the soil surface to impede the rapid downcutting by gully erosion processes (Fitzgerald 1967; Shellberg 2011).

Dissolved nitrogen is a very mobile nutrient and keenly sought by most life forms. Hence it is not common for it to move far in runoff water before being taken up by algae, bacteria, plants or microflora (Devlin *et al.* 2003, Fabricius *et al.* 2005). By comparison, phosphorus is often moved large distances in combined form adherent to sediment particles or as part of the sediment clay material. Such clay is often held in suspension in freshwater all the way to the coast and forms a major part of the visible plume that moves into the reef lagoon from major rivers. Phosphorus in that form can be utilized by algae and seagrass and may affect the local ecology of an inshore reef (Fabricius *et al.* 2005)

Figure 16. Scalded frontage on a saline sodic soil type.

Seagrasses do use nitrogen and phosphorus in water and sediment to their advantage (Lee Long *et al.* 2000), but if the sediment is too dense and persistent, light is restricted to them and they then lose vigour. Free-living and surface adherent algae on the other hand are not generally inhibited by sediment and benefit greatly from nitrogen and phosphorus entrained in sediment plumes. Hard corals can be damaged by excessive amounts of sediment and nutrients in the water (Lough and Barnes 2000), but the effect can differ markedly between different coral types (Fabricius *et al.* 2005). The ability of some corals to recover from excessive coverage by sediment may not always be as poor as was thought a decade ago (Diaz-Pulido *et al.* 2009) with some showing greater capacity to regrow asexually than was originally thought, if favourable conditions follow the initial damage event.

Approach to earthworks

The literature shows that little is known about the specifics of how to rehabilitate D-condition lands in the reef catchments. If land is badly degraded, classed as D-condition, then by definition some sort of mechanical intervention is needed. Where the degradation has not gone so far as to remove all topsoil and seedloads, the country is in C-condition. In this state, the exclusion of livestock alone has been shown to improve condition further and often rapidly (Fitzgerald 1968; Hacker 1989; Williams 1990; WA Rangeland Management Branch 2003). Improved grazing management is all that is required to restore C-condition land to B condition.

Improving land condition can be achieved by mechanical disturbance or earthworks that aim to retain water on the surface for longer so that it can infiltrate, and to minimize the amount of water running rapidly over the eroded land surface in distinct channels. Retaining water for longer on the surface can be achieved by any means that either ponds (Figure 17) or roughens the surface so that rainfall is held where it falls. The rough surface also holds or traps loose seeds so that they can germinate after rain surrounded by persistent moisture. The roughness can even be provided by sticks and logs (Noble *et al.* 1997) that reduce windshear, trap mobile sand and seeds, and slow overland flow of runoff water.

Figure 17. L. Extensive waterponding on flat scalded land (source: Rhodes 1987).

Earthworks to trap water may aim to slow its flow rate, distribute it more evenly or pond it. The extreme case is on flat or very gently sloping land where waterponding behind U- or C-shaped banks holds runoff water for many days on land that has a very slow infiltration rate (Payne *et al.* 2004). The general recommendation is to not pond water deeper than 10-15 cm (Jones 1967; Quilty 1986) so the frequency of 'ponds' is determined by the catchment area needed to provide that water from an average storm event. The ponds may be cascading so that they capture excess from further upslope. There seems to be a difference of opinion about whether the bank should be created by soil scooped out from upslope or downslope of the wall (Jones 1967; Richards 2006). If the surface soil horizon is relatively deep it may not matter but if the excavation exposes a sodic subsoil that may be very inhospitable for plant growth if it is beneath the ponded water. Such exposed subsoil could also act as a starting location for tunnel erosion under the bank. Nonetheless, such badly scalded, sodic land is often where prolonged ponding of rainwater is most successfully used to revegetate land (Quilty 1986). Very slow infiltration rates are overcome by the downward leaching effect of the water that carries much of the sodium deeper into the solum. The surface clay becomes less dispersive and will develop peds and cracks that allow more rapid infiltration of later rainfall and which capture seeds, mobile silt and litter to initiate revegetation and reformation of a friable surface soil layer (Jones 1967; Ringrose-Voase *et al.* 1989).

This process can take years to complete so the bank has to be pushed up much higher than is required for its final form because it will settle down under repeated rainfall events (Jones 1967; MLA 2012). As it settles, some topsoil will wash over the borrow-trench to provide a better plant growth environment, especially if sodic or indurated subsoil was exposed. Every attempt should be made to prevent any sodic subsoil material from ending up lying on top of or on the uphill face of the bank because that will disperse, seal the surface and produce a hostile soil surface in which regenerating plants will be trying to grow. However, revegetation can sometimes occur more rapidly and those ponding areas can be a nucleus from which rehabilitation can expand and also as a seed production area for reseeding other nearby rehabilitation projects (Sullivan 1992 a, b; Payne *et al.* 2004).

On extensive, relatively flat (<2% slope) eroded D-condition land, the current recommended ponding design and bank construction method has been developed from trials in the Fitzroy River region of the Kimberley in WA (Matthews 2013).

A common use of contour and diversion banks is for diverting runoff away from sensitive, bare or gullied areas so that excessive overland flow cannot develop to damage sensitive areas or areas that are undergoing rehabilitation (NT DLRM 2012). Such banks need to be constructed so that captured water is drained away to a location where it enters an existing well-armoured waterway or on to an area where the chances of serious gullying is unlikely in the event of a major storm event. A diversion bank across a minor waterway may also be used to supplement the moisture reaching selected areas of pasture (called waterspreading, Aramac Landcare Group 2000; Cull 1964), but in tropical environments with high intensity rainfall they are prone to delivering so much water at high velocity that scouring of the topsoil is a common, unwanted outcome. Hence using waterspreader banks to 'irrigate' poorly vegetated D-condition land should not be considered. Be aware that the term 'spreader bank' or 'water spreader' is used in publications to describe groundworks that have quite different intentions and bank layouts (Pressland 1977; QMDC 2004; Fletcher 2011).

Banks have also been used in combination with cultivated strips, particularly in the Ord and Fitzroy River catchments of Western Australia. Here the soil is mostly deep, fertile and slopes very low. An opposed disk plough is used to form a low bank on the contour to trap runoff water and upslope of it a strip of land is cultivated with a tyned implement, generally with 3-7 points on the toolbar (Fitzgerald 1968a; Sullivan and Kraatz 2001). Full details of the size of the bank required, the way to follow the contour and the spacing of cultivated strips is given in Fitzgerald (1968), Williams (1990) and Sullivan and Kraatz (2001).

Commencing in 2009, trials of rehabilitation of scalded clay pans, D-condition, in the Fitzroy River region of WA have identified that large capacity graders, Caterpillar G16, are most efficient and economical to build banks for shallow ponding (Figure 18). The ponds and banks require professional design and construction techniques (Fletcher 2013).

Figure 18. Caterpillar G16 grader building pond banks to a proven design along surveyed contours, Fitzroy catchment, WA. (Photo R. Thompson)

A bank design has been developed to afford most opportunity for a long life and to retain sufficient water for a long enough period to provide the best chance of establishing plant cover. The grader blade angle and depth is set to retain topsoil at the top and there are two blade runs on the up-slope side and one blade on the lower slope side. There must be no furrow on the top to reduce chance of the bank collapsing (Fletcher 2013).

Numerous other patterns of banks and cultivation have been experimented with all around the world (FAO 1987). Some are laid out in a checkerboard pattern (Cunningham 1974c), others in spirals, some in circles, many in strips along the contour (Figure 19) (Cunningham 1967) and then some with combinations of such designs (Cull 1964). The height of the banks and any gaps between adjacent segments of banks vary greatly depending on the soil type, the variability of the landscape and vegetation and the slope of the land.

Figure 19. Vegetation still restricted to old spiral furrows on a sodic claypan many years later.

Where roughening of the soil surface is the object of the work, a large array of equipment has also been used as discussed earlier. Chisel ploughing is the most widespread recommended implement and mould-board ploughs are usually explicitly not used for this type of rehabilitation because the surface soil is inverted. Where country is degraded, there is often little topsoil left and the subsoil is often very inhospitable (saline, sodic or impervious) for plant growth and so should not be on the land surface.

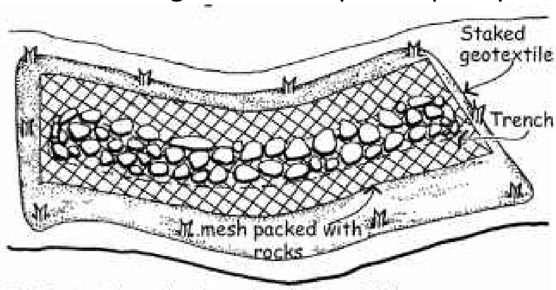
Effects of rehabilitation on runoff water quality

Runoff water from country with limited pasture cover is not always laden with sediment. Hard-setting soils with high cryptogam cover are not very erodible and yet they look bare and may send a bare soil radiation signal to satellite sensors when dry (Burgheimer *et al.* 2006). However, previous studies relying on satellite-sensed information about persistently poor cover have found that a sizeable percentage of 'bare' sites were not bare due to overgrazing (Karfs *et al.* 2009a). Some annual grass areas on shallow soils, especially gravelly surfaced types, appear bare or with low cover in satellite imagery taken in late winter. These areas can have adequate cover in the summer growing period. Sediment loss from cryptogam-covered surfaces is much reduced in many cases even if the infiltration rate is sometimes lower (Eldridge and Greene 1994). Tongway and Hindley (2004) include the degree of cryptogam cover in aspects of their landscape function analysis (LFA) assessment because lack of them indicates surface soil disturbance, except in very loose, sandy soils.

Land that has a better cover of vegetation and surface roughness will normally suffer less erosion because firstly raindrops are mostly intercepted before striking the soil and secondly because overland flow is broken up and generally diminished on hillslopes and river frontages. Rehabilitation seeks to restore better cover on the treated area via better infiltration of incident rain and via reduced runoff and less channeled flow (Rhodes and Ringrose-Voase

1987; Webb 2003). Infiltration is improved via better surface structure and longer residence time on the soil surface. The improved surface structure comes from greater organic matter in the soil surface (Tisdale *et al.* 1978), greater microfauna and fungal activity under the vegetation litter and reduced sorting of surface soil particles into a tightly packed or strongly layered surface (DERM 2011). There are strong feedback loops in this situation because the enhanced infiltration allows more vigorous and prolonged pasture growth and that returns more organic matter to the soil profile via dying roots. The extra root growth also creates potential fine pores and channels in the soil which further enhances infiltration.

In tropical areas, the better rehabilitated pasture growth will initially usually have a sizeable proportion of annual or ephemeral plants that can be replaced over time with perennial species which confer far greater resilience on the vegetation (Fitzgerald 1968). Such pasture filters runoff water and traps heavier sediment so that, if present, soil does not move far from its source. That sediment acts as an enrichment material by potentially providing nutrients, seeds and enhanced water holding capacity at that site. Foraging microfauna will also use the trapped resources for food and shelter if undisturbed by grazing domestic stock. Any sediment that does escape to a waterway will, however, be relatively nutrient rich and of a fine, colloidal nature that is very evident on floodwaters. The nearer the source of sediment to a watercourse the greater its' chance of being entrained in the general water flow and carried long distances from its source. Thus scalded river frontage country seems more likely to supply watercourses with heavy sediment than erosion from adjacent hillslopes, unless that erosion is from existing gullies which have far greater transport capacity.



http://www.lrm.nt.gov.au/soil/management/factsheets

Figure 20. Example of matting along a water course for protection from gully erosion (Fitzroy catchment, Qld).

Figure 21. Rock weir and drop structure used to stabilise gullies.

Gullies pose particular problems in zones of high overland flow because they greatly increase the transport capacity of the water and the erosive power of the water is further concentrated. They will almost always require an engineered approach to their stabilization and that is expensive. In areas where mining is an established industry, there will be technology and equipment at hand that can address the problem, especially rock and riprap (woven geotextile fabric) (Figure 20). Streeton *et al.* (2013) have described a situation where a small stream catchment of 2500 hectares was brought under a rehabilitation programme to address ongoing incision of the dispersive subsoil in a grazed landscape. They constructed small porous rock weirs (Figure 21) at strategic places that trapped sediment in conjunction with fencing off of the waterway to prevent grazing except for short periods each year. The 11 weirs along a 13 km stretch of watercourse were up to 1 metre high and cost on average $1800 each. These weirs will require re-building over time as the sediment backs up behind them. After six years there was reduced sediment and the flow spread wider across the floodplain. Sediment reaching the lake was mostly fine particle sizes, particularly fine sand.

Figure 22. Bad gully erosion after excessive poisoning of trees in a susceptible landscape.

The distribution of bare areas across hillslopes (Figure 22) can have a big influence on the amount of sediment that reaches the local watercourse (Post *et al.* 2006). Connolly *et al.* (1997b) stated that scattered cover over a whole catchment was more beneficial in reducing storm runoff near Bogantungan, central Qld, than intensive cover development on the worst bare patch of their catchment. Such an appraisal may depend on whether only hillslope erosion was involved or whether there was significant gully erosion happening as well.

Removal of stock alone produced such an outcome on their small Bogantungan catchment but they provide no data about the amount of sediment that was entrained in the runoff under the various treatments and storm events.

Identifying the quantity of sediments and nutrients moving down streams and their source within the landscape is one step in locating areas to concentrate improved soil cover management. Turner *et al.* (2013) have identified river catchments that deliver the highest rates of suspended sediments, nitrogen and phosphorus nutrients and pesticide loads into the GBR lagoon. These authors reported that the Fitzroy and Burdekin River systems combined, represented 82% of the catchments monitored, but they generated the highest loads of suspended solids and nutrients including 66% of the total suspended solids (13 million tonnes), 73% of the total phosphorus (approximately 23,000 tonnes) and 56 per cent of the total nitrogen (approximately 57,000 tonnes) loads over the high rainfall summer of 2010-2011.

Overall, where cultivation is used to prepare rough ground for sown pasture establishment, there is an early risk of pasture establishment failure and enhanced sediment loss from the bare ground, despite the greater infiltration and retention capacity of the land. Once pasture is established, runoff and sediment movement should be reduced unless significant gullies develop due to failure of contour banks or similar structures for ponding or controlling runoff water. If that occurs, repairs should be carried out immediately to correct the problem. Such failures are more likely to occur where dispersible subsoil is exposed at the site. The failure may take the form of deep rills (<30 cm deep, can be removed by cultivation) or a gully (too large to be removed by cultivation alone) but could also occur as tunnel erosion where surface soil largely stays in place and a tunnel forms in the subsoil beneath.

There is scant data about changes in runoff and sediment loads from rehabilitated grazing land. Most comes from rehabilitated minesites (Carroll and Tucker 2000) which often differ fundamentally by having no bedrock close to the soil surface, such as in Central Qld coalfields or sand mining operations. Some information comes from a comparison of existing cropped land with adjacent areas newly sown to pasture (McKergow *et al.* 2004a, b) but the original starting situation was not D-condition grazing land. In most mining nowadays, topsoil is stripped off, stockpiled and then returned over the processed sand or reshaped minespoil (Silcock 1991). There has been a lot of work done on the topic of rehabilitating such land with vegetation but the data is often not released for scientific scrutiny. One mine type that does have bedrock relatively close to the rehabilitated surface is bauxite mining in Cape York. Final land use objectives control the type of vegetation replanted but pastures are most effective in minimizing further erosion and sedimentation of streams. Trees often do well where there is a deep profile with high water storage capacity but they are very slow to provide adequate ground cover which is the main need in order to minimize sediment entrainment to adjacent streams. Pastures do this much better but they also compete strongly with tree seedlings and can kill them and hence leave elevated landscapes more exposed to strong winds than is desirable. However, the management of those pastures in the long-term becomes a major issue with burning or overgrazing quickly converting sloping land to highly erodible landscapes until high pasture cover is returned.

The important message from the numerous minesite rehabilitation experiments and projects done around Australia on a wide range of landscapes and soils is that generalities about rehabilitation methods are very unreliable and the same will apply to the rehabilitation of badly degraded pastoral lands. Underlying geology, soil type, landform, seasonal rainfall, climate, desired final vegetation and proposed final land use all interact to mould the rehabilitation methods used and the timeframe over which the outcome may be achieved. Ideally erosion and runoff from the degraded land should retreat to near normal rates for that location within 1-3 years, but 10 times that duration may be required and, even then, the ability to use the land for an income-deriving purpose may be severely compromised in perpetuity.

Effects of rehabilitation on rates of soil erosion

The rate of soil erosion is controlled principally by the amount of runoff from the site and the amount of runoff is strongly influenced by the amount of rainfall received (FAO 1991). The nature of the surface ground is also important because it determines how easily the earth particles are mobilized in preparation for transportation by runoff (Bartley *et al.* 2006). If the earth is poorly aggregated due to lack of organic matter or highly dispersible due to a high proportion of sodium in the exchangeable cations, then rainfall will easily disaggregate particles and ready them for transportation in runoff flows. The roughness of the ground also is important because that influences the ease with which local runoff starts to occur prior to gravitational flows combining numerous local flows into defined channels of flowing water that have much greater capacity to transport sediments.

Hence, all rehabilitation manuals emphasise the need to have a rough ground surface (Fitzgerald 1969; Carroll and Tucker 2000). The second main rehabilitation goal is achieving as rapid a rate of cover generation as possible. If that is achieved, other landscape factors such as slope become far less critical (Carroll and Tucker 2000). Carroll and Tucker showed that until a good level of cover was achieved, erosion rates on minespoil was high irrespective of whether the surface was covered with soil as opposed to raw minespoil and irrespective of the soil type spread on the ground. However, while the ground was bare, the erosion rate was proportional to the steepness of the slope. They also demonstrated that the continued existence of high levels of cover (>80%) was essential after the bare minespoil had been successfully well-vegetated and stabilized. A fire that removed the ungrazed, dense pasture allowed a significant erosion event to occur immediately afterwards, before the pasture had regenerated to a high cover level (Carroll and Tucker 2000). This data is for a minespoil that had no inherent geological formation or soil profile but does highlight the potential risks for rehabilitated pastoral lands if grazing or wildfire was to remove a large proportion of the re-established pasture. On natural pastures, burning a good pasture cover does not necessarily lead to a high runoff or erosion rate (Silcock *et al.* 2005, page 330), but in that case the full natural soil profile still existed and good biological activity was present in the soil. By comparison, rehabilitated minespoil takes many years before starting to accumulate organic matter in the ground and to achieve landscape functioning similar to a natural pasture (Tongway and Hindley 2004).

In between these extremes are deep alluvial sediments that are vulnerable to gully erosion if the topsoil cover is removed (Shellberg 2011). Lack of a rock substrate allows any rill or gully to continue to be scoured out deeper and deeper where there is sufficient flow of water. Those gullies have steep sides that do not readily revegetate and hence remain vulnerable to erosion at any time, either by surface drop impact or wash from the adjacent land surface or by undermining of the bank by rapidly flowing water. Shellberg has documented this for the Mitchell River catchment in Cape York.

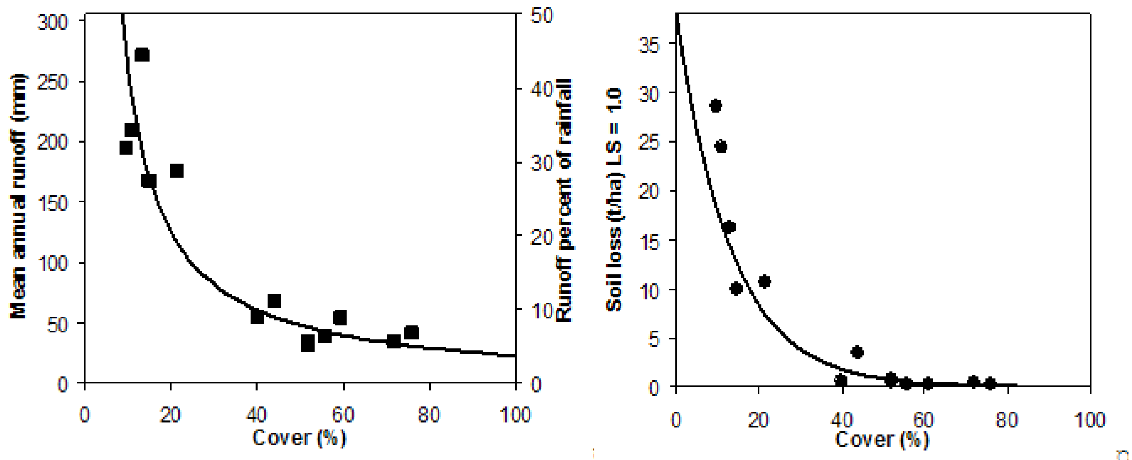


Figure 23. Modelled relationships between ground cover and runoff for native pasture in central Qld (Silburn pers comm.).

The rate of sediment loss after vegetation has been re-established well on badly degraded land has only been measured in a few places, mostly on minesites. In general the effect conforms to the Universal Soil Loss equation where cover, soil surface type and slope are major controlling factors for any given rainfall event (which drives the erosivity of the precipitation). The relationship is strongly curvilinear for cover levels between zero and 40% (McIvor *et al.* 1995; Carey and Silburn 2006), and above about 40% is much nearer to linear with a much decreased rate of change with increasing cover (Figure 23). The curved part of the relationship at low covers has a steepness determined by the erosivity of the surface soil and that is controlled by a combination of soil aggregate stability and the degree of surface cover by cryptogams such as blue-green algae, lichens, liverworts and mosses (Greene and Tongway 1989; Eldridge 1993; Bowker *et al.* 2008). Research has shown that heavy grazing pressure reduces the extent of cryptogam cover due to a combination of hoof impact and exposure to strong direct sunlight and winds (Eldridge 1993).

In some cases the slope of the erosion curve is much nearer to linear to over 80% cover (McIvor *et al.* 1995), probably because several factors are then interacting (cover distribution, cover type, soil fauna and surface roughness) and no single factor is dominating the outcome which was only producing low levels of sediment. For very large rainfall events, cover becomes only a minor factor because the infiltration capacity of the soil is far exceeded and depth of overland flow creates temporary flowpaths that can shift rapidly and thus alter the main factors driving erosion at a catchment scale (McIvor *et al.* 1995; Bartley *et al.* 2006). However, the relationship changes completely if tunnel erosion begins and such erosion is common on mine rehabilitation sites and also on some sodic soils (Silburn 1994; Boucher 1995). Once tunneling leads to gully formation, the rate of soil loss can increase dramatically and the spatial progress of the gully head/s can become very unpredictable and complex to control (Wilson *et al.* 2008b).

How rapidly will rehabilitation efforts yield positive results?

The rapidity of the improvement in runoff and sediment yield reduction depends very much on the rainfall and seasonal conditions in the first growing season after treatment. If very favourable rain comes soon after the disturbance treatment and seedlings establish quickly, cover is rapidly created and all its benefits follow. This happened for Hall (2013b) at 'Spyglass' north of Charters Towers in the above average rainfall summer of 2011-12, but did not often occur in the Ord River and Fitzroy River (WA) areas of NW Australia (Fitzgerald 1968a; Novelly and Watson 2004). Many years went by after rehabilitation works began in the dry years of the 1960s in Western Australia before good cover levels were achieved. Satisfactory pasture cover only occurred after sowings were carried out in wet years. However, it is important to note that Hall's rapid first years rehabilitation success did not apply to one particular soil type, a sodic dermosol, and that weakly perennial grasses like Indian couch (*B. pertusa*) suffered significant later deaths early in the second summer due to a very late start to the wet season. In contrast, the eventual 'success' that came in WA was provided by strongly perennial grasses such as buffel and Birdwood grasses (*Cenchrus* species) and ribbon grass (*Chrysopogon fallax*) (Figure 24 a and b).

Figure 24. Strongly perennial tropical grasses: a. Buffel grass; b. Ribbon grass.

Sometimes bush grass hay or cereal straw is spread over the soil surface after cultivation (Hall 2013b) to provide the initial critical cover and to prolong the period of surface soil moisture on very bare, scalded areas. This encourages insect and micro-organism activity, as well as enhancing seed germination and possibly seedling survival. It is a very slow procedure to get a sufficient thickness of straw spread and it is initially prone to loss through whirly-winds and overland flow until it is 'stuck' to the soil by mixing with wet silt. The straw does greatly reduce the damaging effects of raindrop impact and can significantly slow overland flow from small storms once it has bound with the surface soil. The technique is most often used on mine rehabilitation sites and urban landscape restoration where the expense can be justified.

Critical though vegetative cover is to initiating long-term site rehabilitation, it is many more years before the cover on severely degraded land is of sufficient permanence and durability that normal grazing management might be resumed. In the first year, vegetation is often dominated by annual or ephemeral plants derived from seed that existed already in the degraded country and those plants may be almost entirely lost during the succeeding dry season. Persistent perennial species are needed to be there, alive, when the first storm rains of the next wet season arrive. Living crowns reflect the existence of sturdy, live, deep roots to hold soil together against raindrop impact and against overland flow. Then the reshooting crowns will provide further vegetative cover much more rapidly than that which may arise from germinating seedlings (Silcock 1981). The living crowns also shelter small fauna that burrow in the soil and thus provide pores for rapid moisture penetration (Bowker *et al.* 2008) and soil aeration. Species that are typically sown to initiate pasture rehabilitation are strongly perennial (e.g. buffel grass) and mostly grasses because they provide greater perennial crown cover compared to legumes such as the stylos (*Stylosanthes* spp.). An exception is kapok bush (*Aerva javanica*), a successful rehabilitation species in the Ord River (Novelly and Watson 2004), and that is partly due to its prolific seeding nature and suitability to the local soil types.

The sort of perennial plants that do not produce an adequate long-term rehabilitation result are species like *Enneapogon* spp. (bottlewashers), *Sporobolus caroli* (fairy grass), *Chloris divaricata* (windmill grass) and many wiregrasses (*Aristida* spp.) because, though nominally perennial and easy to establish, they are only short-lived perennials that do not provide enough coarse bulk to persist during droughts or in the face of wildfires and regular grazing (Figure 25). They are free seeders and establish dense populations under favourable conditions but have small crowns and weak roots. Indian couch grass presents similar issues despite its widespread colonization of degraded lands in north Queensland (QCL 2012). The former grasses are sometimes adequate for early ground cover but have to be followed with strongly perennial plants shortly after. Commercial seed supplies of such plants are also non-existent, except for Indian couch.

Figure 25. Sparse small-statured, weakly perennial tropical grass on an inhospitable dermosol soil.

There are annual or weakly perennial native forb species that can provide an interim cover to trap litter, grass seeds and fine soil and thus potentially facilitate establishment of better perennial species. Tarvines (*Boerhavia* spp.) behave similarly (Figure 26) and have the advantage of being strongly perennial but the disadvantage of being palatable. Pigweeds

(*Portulaca* and *Trianthema* spp.) are early seral plants that can establish on poor quality eroded soils, including more favourable areas of dermosol soils that can be inhospitable for desirable perennial grasses.

Figure 26. Native non-grass species *Sida* and *Boerhavia* respectively that can colonise bare, scalded soils in fair seasons.

Bradshaw and Chadwick (1980, page 261) talk about the need for "ecological ingenuity" in the rehabilitation of degraded land and the incorporation of specially chosen local or native species is a clear example of that approach. It may require the development of new knowledge and ways to collect and grow seed of selected plants rather than using readily available commercial sources but the long-term outcome may be far better.

If re-establishing vegetative cover continues to prove nearly impossible on sodic soils, nature would suggest that 'burrs' such as *Salsola kali* (soft roly-poly), *Sclerolaena birchii* (galvanized burr) and *Sclerolaena bicornis* (goathead burr) could be considered (Figure 27), especially in the more southern inland catchments. Seed could be harvested and hammer-milled elsewhere to make it more readily spread over the rehabilitation area (Foster and Godwin 1995).Such a strategy would require a follow-up plan to eventually replace these prickly pioneers by more desirable perennial grasses. However, they are by nature episodic in their pasture dominance and can be suppressed by healthy perennial grassy pasture.

Figure 27. Ephemeral prickly native *Sclerolaena* species that might be considered for an initial soil stabilization role.

After establishing, many appropriate perennial grasses are slow to develop a substantial crown in semiarid environments and require consecutive good growing seasons to develop a crown of 10-20 cm diameter. One of the slowest perennials to develop a large crown is *Bothriochloa ewartiana* and others including *Paspalidium* spp., *Digitaria brownii* (cotton panic), *Astrebla* spp. (Mitchell grasses) and *Eulalia aurea* (silky browntop). We found no published information about the speed of crown development of most of these valuable perennial grasses. Tussock grasses are not traditionally favoured for colonizing scalded land because the rate of expansion from a sparse initial stand is slow, compared to that of stoloniferous species. After poor establishment conditions, even a sparse stand of plants of stoloniferous grasses such as *Sporobolus mitchellii* (rat's-tail couch), creeping bluegrass (*Bothriochloa insculpta*), Indian couch (*Bothriochloa pertusa*) and Pangola grass (*Digitaria decumbens*) can spread in the first few years to provide a reasonable degree of ground cover under average seasonal conditions.

Rooting and new crown development along the stolons can be poor unless good seasonal rains occur that allow the nodal roots to fully penetrate the soil. Then the new crowns can function independently of the parent crown. There is also an apparent physiological problem that restricts the occurrence of native stoloniferous grasses in Australia that is probably related to the extreme temperatures reached in the dry months at the soil surface. The growing point buds are too exposed directly to temperatures that exceed 50-70^{o}C compared to equivalent growing primordia in rhizomatous crowns such as Mitchell grass and ribbon grass, or tussocked crowns such as on *Themeda* species (e.g., kangaroo grass). In the former, the buds are covered by 3-5 cm or more of dry soil and in the latter the protection comes via shading of both the primordia and the adjacent dry soil by dead sheathing leaf bases of old leaves.

Profitability of rehabilitation of D-condition land

Campbell *et al.* (2006) caution against a "one size fits all" approach to sustainable land management prescriptions in variable climatic regions after investigating many of the factors that impinge on the decision making process of land managers. They looked at discount rates, property rights, and market stability factors as well as grazing pressure issues. It is unlikely that simple policy measures based around modelled economic scenarios will achieve the desired water quality outcomes for the GBR.

No publications reported with credible data that the rehabilitation of D-condition pasture lands was commercially profitable. The Ord River regeneration program has been judged successful in minimizing the erosion in most parts of the catchment (Novelly and Watson 2004), but no robust economic assessment has been published on that scheme, such as a cost/benefit analysis. Politically it was important to halt the erosion and to revegetate the eroded country to protect the irrigation capacity of Lake Argyle. The cost has been amortised against a wide variety of government programs aligned with development of irrigated cropping industries in northern Australia. Reducing potential silting of the Ord River Dam from extensive grazing lands was a Government priority for this rehabilitation programme. Some producers have undertaken small-scale rehabilitation works (FBA 2006b, Finlayson and Finlayson 2011; Figure 28) and express satisfaction in the improvement that they have made, but the costs are not well documented.

Figure 28. A published initial success at rehabilitating badly degraded country at a local scale (Finlayson and Finlayson 2011).

Another economic assessment approach is the modeling undertaken by Star and Donaghy (2010). They took the best opinions on likely cost and benefits, timelines for achieving a commercially useable pasture, augmented by published research site data, and historical climate data. They did this for several landtypes and for two different business operations, a sustainable breeding herd and a steer fattening operation. That found it was not generally economical to undertake rehabilitation on treed landscapes in scalded D-condition whereas it sometimes was on treeless scalded country.

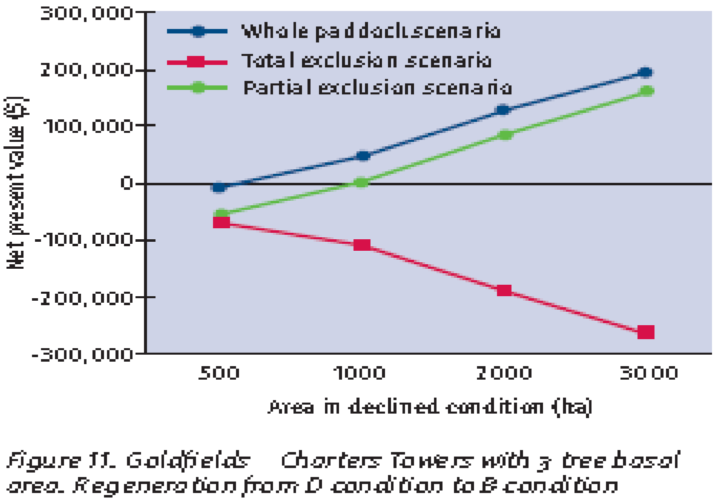


Figure 29. NPV over 20 years for various rehabilitation scenarios (Star and Donaghy 2010).

The modeled economic outcome over 20 years for rehabilitation of lightly timbered D-condition granitic country near Charters Towers to B-condition is shown in Figure 29 (Star and Donaghy 2010). It illustrates that fencing and providing water to the un-degraded part of a paddock (total exclusion) was never economic, but that excluding stock from the whole paddock during the wet season, along with other improved grazing management such as occasional burning, could be economic especially if the paddock size was large. The potential economic benefits of improved grazing management were greater if the proportion of the paddock that was in D-condition was great (whole paddock scenario).

An assumption by Star *et al.* (2011) in further calculations was that the 'delivery ratio' of sediment to the GBR lagoon was 12.5% for all treatments which is higher than many other reports suggest of 5-10% (Bui *et al.* 2011). We found no report that nominates how much that ratio may be affected by grazing management and paddock layout. Bartley *et al.* (2006) show that the location of the measuring point in relation to scalded versus well-covered soil had a huge impact on the concentration of sediment recorded leaving a small catchment. Star and Donaghy (2010) conclude that more biophysical information is needed to assist sensible funding decisions and the delivery ratio is one uncertain parameter. Given that good pasture condition is regarded as minimizing the amount of sediment moving off a small catchment (McIvor *et al.* 1995; Silcock *et al.* 2005; Orr and Burrows 2011), an improved sediment delivery ratio could be expected from a well-managed pasture depending on how close the paddock was to a major stream or transport corridor where gullies carrying sediment would be most common.

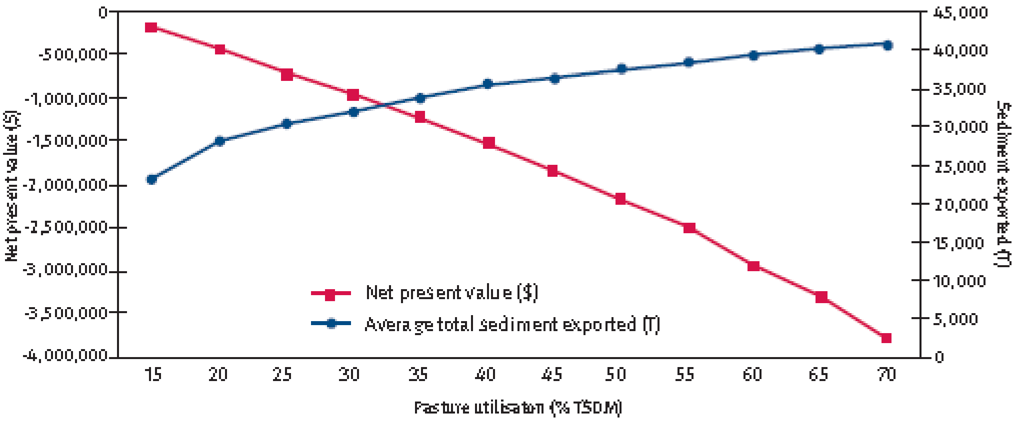


Figure 31. Goldfields Charters Towers, C start condition, 3 tree basal area

Figure 30. Star and Donaghy (2010) showing that even rehabilitation of some C-condition land may never be commercially attractive in terms of NPV even if the sediment reduction outcome is acceptable.

For C-condition pasture, the figure from Star and Donaghy (2010) (Figure 30) shows that no normal pasture utilization rate was profitable in the long-term. Given that Karfs *et al.* (2009a) report that 36% of Burdekin catchment sites inspected were rated as C-condition, this is not an encouraging economic picture for the cattle industry in a large part of the GBR catchment. The calculated 'opportunity cost' of soil erosion increased from $8/tonne at 15% pasture utilization rate to $313/tonne at a 50% long-term utilization rate. Pasture in B-condition had optimal profitability at 25% utilization rate so, presumably, D-condition pasture would not generate any appreciable long-term profit even at very low levels of use, such as 5%. Such a position seems to be believed by the cattle industry in northern Australia if current changes in management philosophy are an indicator (Stocktake Plus 2013; Grazing BMP 2013).

Other economic analyses by Star *et al.* (2011) and Star *et al.* (2012) present a complex range of modelled outcomes that are highly dependent on the assumptions made. Though the basic objectives are the same in all three papers (reduce sediment delivery to the GBR lagoon) and the region is the same, there is no unifying message coming through because the question being tested varies in each case. An NRM Group information sheet (FBA 2010) also addresses this topic, probably based on Star's studies, and presents similar findings but uses different baseline cost data.

The economic outcome depends on what benefits were accrued in the first 1-2 years after treatment. If poor seasons follow, the money spent may be lost. If good seasons follow, the response may be rapid in terms of cover and erosion reduction (Hall 2013a, b), but it takes more than a few years to return the land to a stable enough pasture to permit routine grazing. For poor condition land close to watercourses there is the risk that exceptionally good rains could flood the new pastures and decimate them either by scouring the unstable, ripped surface soil or by killing the pasture via prolonged immersion. Sedges are some of the best herbaceous plants for tolerating prolonged flooding but there are none that are available as commercial seed. Of the more waterlogging-tolerant commercial pasture species, few are legumes suited to eroded soils and the likely grasses have poor tolerance of severe moisture stress, e.g., cv. Tully (*Brachiaria humidicola*) and para grass (*Brachiaria mutica*). Pangola grass (*Digitaria decumbens*) is more tolerant of short dry periods, but it has to be planted vegetatively which complicates the task of getting it established. The stoloniferous *Digitaria milanjiana* (cv. Jarra) has potential for rehabilitation of higher rainfall areas in eastern Queensland, and cv. Strickland may have a role in drier environments.

A recent assessment of costs for works aimed at rehabilitating badly scalded country at a remote location in the Kimberley was put at $149 per hectare for a 20 ha site (WA Agriculture Authority 2011). That cost included construction of banks to control water flow, ripping of some of the ground and the purchase of sorghum seed. The seed costs could be higher for other perennial pasture grasses.

An economic analysis tool (Land Reclamation Economics Spreadsheet) has been developed for landholders to calculate their own costs and potential benefits from rehabilitation works (Moravek, 2013) and it is available on the FutureBeef (DAF, Queensland) web site.

Relevance of review learnings for various audiences

Financial incentives from Government and community groups have a significant part to play in motivating action by land managers. However, there has been some criticism that monies spent in the past have not been effective in reducing pollution of waterways and the GBR (Star *et al.* 2012). Action aimed at achieving desired outcomes has occurred, but there is only weak evidence that on-ground work has delivered meaningful benefits. The grazing lands in coastal north Queensland have been blamed for most of the sediment arriving in the GBR lagoon, especially in early days of 21st century, leading to programs to preserve reef integrity and biodiversity. However, a recent study has shown that gully erosion from many sources is a bigger contributor than first thought (Wilkinson *et al.* 2012) and that sediment mobilized many decades ago, even over a century ago by early mining activity, is still entrained in riverine environments or continuing to contribute pollutants to waterways (Streeton *et al.* 2013). Similarly, heavy grazing of river frontages with the only permanent waters occurred in the drought years of the early 1900s when there was no road transport or supplementary feeding options to lighten grazing pressure and that caused many erosion problems. Erosion damage caused in this era, especially to river banks, may still not be rehabilitated to the present day. Likewise, ongoing improvements in grazing land management to address the issues will not reverse overnight the consequences that currently exist from prior inappropriate land management.

There is now a greater range of data and processed information (Thorburn and Wilkinson 2012) available on improving water quality to the formers and implementers of policy for making decisions on the allocation of scarce public and private resources (Brodie *et al.* 2012).

There are some essential activities in a land rehabilitation project:

1. Adequate persistent vegetation cover has to be returned to the denuded land,
2. Grazing pressure has to be substantially reduced and usually completely removed initially from the affected area,
3. Ongoing grazing management and monitoring of the condition and erodibility of the site is required.

After those three essentials, other actions will depend on the local situation and the specific goals set for achievement.

Sullivan and Kraatz (2001) provide a summation of the experiences of the Northern Territory in undertaking rehabilitation of badly degraded land (See Figure 31 for red soils and Figure 32 for clay soils). To address the uncertainties and the diversity of situations, they constructed a decision tree (pages 108 and 109 respectively) to help those intending to undertake rehabilitation to systematically assess their situation and options so that they minimized their risks and costs and understood the follow-up management required. These authors also discuss the strengths and weaknesses of a wide range of implements for cultivating degraded land and their appropriateness for different soil types. This approach can be used as a guide in planning rehabilitation strategies for degraded landscapes in the GBR catchments of Queensland.

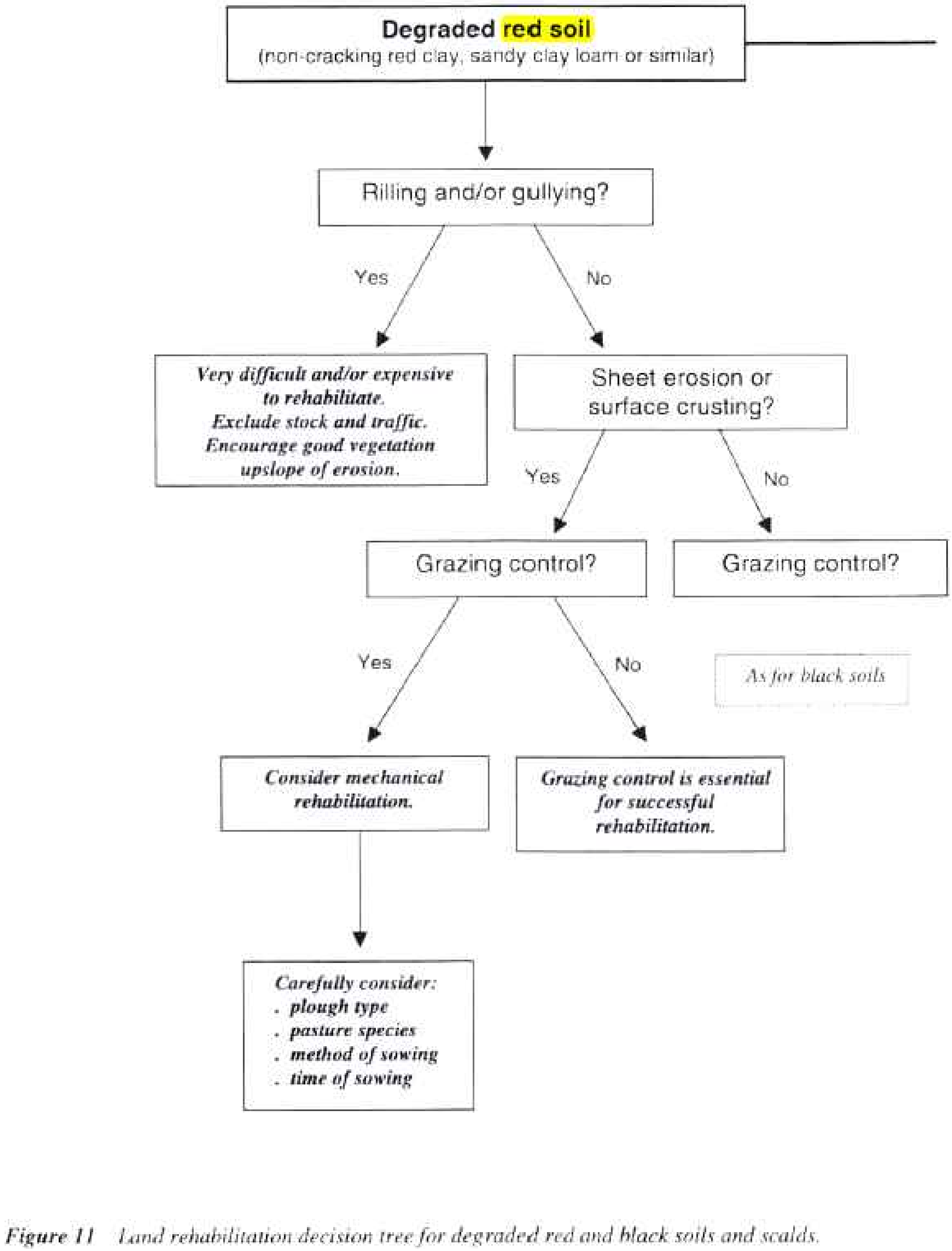


Figure 31. Decision tree to select the most appropriate rehabilitation strategy for degraded non-cracking red clays, sandy clay loams and similar soils in pastoral land in the upper Northern Territory region (Sullivan and Kraatz 2001).

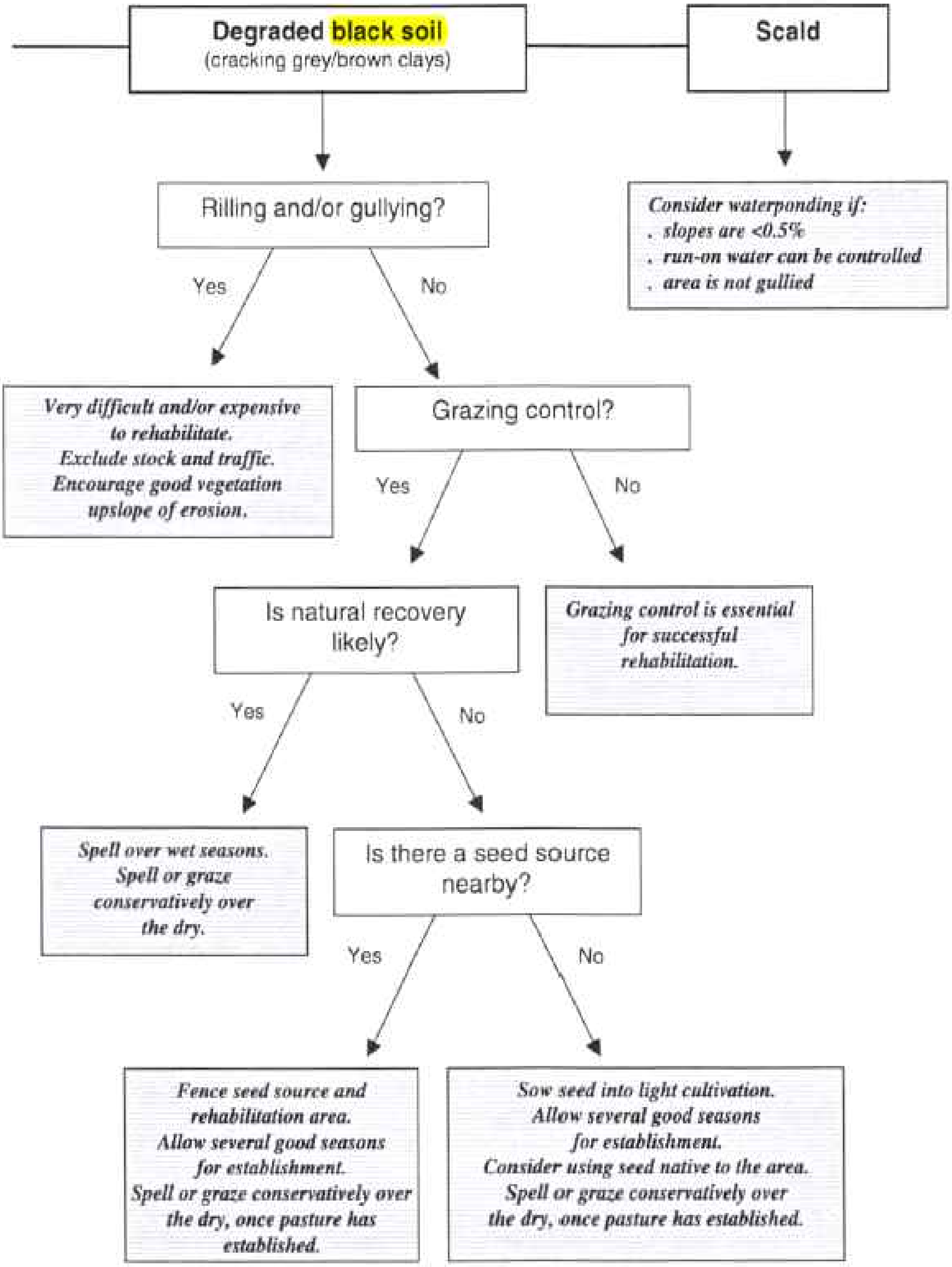


Figure 32. Decision tree to select the most appropriate rehabilitation strategy for degraded cracking clay and loam soils in pastoral land in the upper Northern Territory region (Sullivan and Kraatz 2001).

A list of reading materials used in preparing this review and for referral to by those looking for information on rehabilitation of land is included in Appendix A. Many references are supporting information or background scientific knowledge that underpins why certain steps need to be taken to ensure greater rehabilitation success.

Appendix B shows where there are direct links between the six specific objectives of this project and the references and reading list reported in Appendix A.

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APPENDIX B. References providing evidence to the six project objectives

Published information source	1 Social + Economic Motivat'n	2 Barriers to rehab	3 Improve water quality	4 Reduces erosion	5 $ Costs Benefits incentives	6 Time lags >improve
	Objective					
Abbott (2009)		✓				
Abbott *et al.* (2008)	✓	✓			✓	
ABC (2011)					✓	
ABC (2012)	✓				✓	✓
Abernathy and Herbel (1973)		✓				
Allen *et al.* (2001)	✓	✓			✓	✓
Aramac Landcare Group (2000)	✓				✓	✓
Ash *et al.* (2001)	✓					✓
Ash *et al.* (2011)				✓		✓
Bartley *et al.* (2006)		✓		✓		
Bohnet *et al.* (2007)	✓					
Boucher (1995)		✓			✓	✓
Bowker *et al.* (2008)				✓		
Bradshaw and Chadwick (1980)	✓	✓	✓	✓		✓
Branson *et al.* (1966)				✓		✓
Bridge *et al.* (1983a)						✓
Brodie *et al.* (2012)						✓
Brooks *et al.* (2009)			✓	✓		✓
Brown (2004)	✓				✓	
Bruce (2011)	✓	✓				
Bui (1997)	✓					
Carey and Silburn (2006)		✓	✓	✓		

	Objective					
	1	**2**	**3**	**4**	**5**	**6**
Carroll and Tucker (2000)		✓	✓	✓		✓
Catchments and Creeks (2010)				✓		✓
Chewings (1990)	✓	✓			✓	
Chilcott and Silburn (2000)				✓		✓
Chilcott *et al.* (2003)	✓					
Connolly *et al.* (1997a)				✓		✓
Connolly *et al.* (1997b)						✓
Cull (1964)	✓			✓	✓	
Cunningham (1967)		✓				✓
Cunningham (1974b)					✓	✓
Cunningham (1974c)		✓				
DAFF (2011)					✓	
DERM (2011)				✓		✓
Erskine and Saynor (1996)				✓		
Fabricius *et al.* (2005)	✓					
FAO (1987)				✓		
FBA (2006)			✓	✓		
FBA (2006a)	✓			✓	✓	
FBA (2006b)	✓				✓	
FBA (2007)			✓	✓	✓	✓
FBA (2011)	✓	✓			✓	
Finlayson and Finlayson (2011)	✓				✓	✓
Fitzgerald (1967)	✓					
Fitzgerald (1968)		✓	✓	✓		✓
Fitzgerald (1968a)		✓			✓	✓
Fitzgerald (1976)	✓			✓	✓	

	Objective					
	1	2	3	4	5	6
Fitzpatrick *et al.* (1995)	✓					
Fletcher (2013)					✓	✓
Ford *et al.* (2005)				✓		
Grazing BMP (2013)	✓	✓			✓	
GRDC (2010)		✓				
Greiner and Lankester (2005)	✓				✓	
Hacker (1989)	✓			✓	✓	✓
Hall (2013a)						✓
Hall (2013b)						✓
Hughes *et al.* (2010)				✓		✓
Johnson and Zhang (2012)		✓				
Johnstone (1992)	✓					
Karfs and Trueman (2005)	✓	✓				
Karfs *et al.* (2009)	✓				✓	
Lang and McCaffrey (1984)				✓		
Lang (1979)			✓	✓		
MacLeod and Johnston (1990)	✓	✓			✓	
McIvor *et al.* (1995)			✓	✓		✓
McKeon *et al.* (2004)	✓					✓
McKergow *et al.* (2004a)			✓	✓		
McKergow *et al.* (2004b			✓	✓		
Melville (1994)	✓	✓				✓
Mitchell *et al.* (2009)			✓			
MLA (2012)				✓	✓	✓
Munda and Pater (2003)		✓				✓
Naidu *et al.* (1995)					✓	

	Objective					
	1	2	3	4	5	6
Nimmo (2011)		✓				
Noble *et al.* (1997)			✓	✓		
Novelly and Watson (2004)	✓			✓		✓
Novelly and Watson (2007)				✓		✓
NT DLRM (2012)				✓		
O'Reagain *et al.* (2005)						✓
Orr and Burrows (2011)				✓	✓	
Orr and Phelps (2013)						✓
O'Sullivan and Peck (2008)		✓			✓	
Payne *et al.* (2004)				✓		✓
Post *et al.* (2006)			✓	✓		
Powell and Martens (2005)	✓	✓	✓		✓	✓
Purvis (1986)	✓					
Qadir *et al.* (2007)					✓	✓
QMDC (2004)	✓			✓	✓	✓
Quiggin (1997)		✓				
Quilty (1986)		✓			✓	✓
Richards (2006)						✓
Ringrose *et al.* (1989)						✓
Roberts *et al.* (2001)	✓					
Rodriguez *et al.* (2010)	✓					
Roebeling and Webster (2007)	✓			✓		
Roebeling *et al.* (2004)	✓	✓			✓	
Roth *et al.* (2003)			✓	✓		
Ryan (1981)	✓	✓		✓		✓
Sandral and Paton (2009)	✓	✓				

	Objective					
	1	2	3	4	5	6
Sharpley *et al.* (1996)			✓	✓	✓	✓
Shellberg (2011)	✓	✓	✓	✓	✓	✓
Silburn (1994)			✓	✓		✓
Silburn *et al.* (1992)				✓		
Silcock (1991)				✓		
Silcock *et al.* (2005)				✓		
Smith *et al.* (2005)	✓	✓	✓	✓	✓	
Star and Donaghy (2010)				✓	✓	
Star *et al.* (2011)	✓				✓	
Star *et al.* (2012)	✓	✓			✓	
Stieglitz (2005)			✓			
Stocktake Plus (2013)	✓	✓			✓	
Streeton *et al.* (2013)				✓		✓
Sullivan and Kraatz (2001)				✓	✓	✓
Sullivan (1992a)	✓	✓		✓	✓	✓
Taroom Landcare Group (2012)	✓					
van Grieken *et al.* (2011)	✓	✓			✓	
WA Rangeld Mgmnt Grp (2003)	✓	✓		✓	✓	✓
WA Rgld Mgmt Br (1981)	✓	✓		✓	✓	✓
Wang and Lindner (1990)	✓				✓	
Wiedemann (2005)	✓					
Wilkinson and Brodie (2011)					✓	
Williams (1990)	✓					
Wilson *et al.* (2008a)	✓			✓	✓	
Yitbarek *et al.* (2012)	✓					