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Department of Agriculture
Government of Western Australia

TECHNICAL ASSESSMENT OF NATURAL RESOURCE MANAGEMENT THREATS AND OPTIONS IN THE NORTHERN AGRICULTURAL REGION OF WESTERN AUSTRALIA

Compiled by Lorinda Hunt and Gary Patterson

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Resource Management Technical Report 289

Technical assessment of natural resource management threats and options in the northern agricultural region of Western Australia

Compiled by Lorinda Hunt and Gary Patterson
for the Northern Agricultural Region
Agricultural Resource Management Group

Department of Agriculture, Western Australia

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¯State of Western Australia, 2004.

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CONTENTS

INTRODUCTION

This document has been compiled to analyse the intrinsic risk of soil, land and water degradation (bio-physical agricultural resources) within the Northern Agricultural Region (NAR). Little data is currently available on the actual areas of land affected by most issues. Instead the results of regional land resource surveys have been interpreted to calculate the area susceptible to many of the issues based on the characteristics of the soils and landscape, where it is available. Climate variability and regional land use practices will influence the severity and extent to which an issue impacts on agricultural land.

The methods used to make the interpretations are documented in Van Gool, Moore and Tille (in prep.) and are held within the Department of Agriculture's Map Unit Database. The calculations are based on the area of privately owned agricultural land within the region, as defined by National Land and Water Resources Audit (NLWRA) data. The estimates of areas are presented for each of the four subregions within the NAR.

Each natural resource management issue is covered in five sections:

1. **Cause:** A description of what processes and influences are involved in relation to the development of the threat in question.
2. **Extent:** Briefly describes the nature and extent of susceptibility to the land resource issue based on the characteristics of the soils and landscape.
3. **Impacts:** A brief description explaining why the issue is of concern, its causes and how it affects agriculture and the environment. For more details, readers are pointed towards the relevant references.
4. **Management options:** The on-ground actions that are known to be effective in managing the issue. Management options have been classified according to Salinity Investment Framework principles, i.e. all options are aimed at recovering or containing the problem or allowing land managers to adapt to living with the problem.
5. **Effectiveness:** The potential effectiveness of each management option is summarised, with appropriate references provided. References are important because they identify where the science supports the use of the management actions/options. They are also important to identify where little or no information is available on the effectiveness of management actions.

ISSUE 1: ACID GROUNDWATER

Cause

Acid groundwater usually occurs in areas of good rainfall and waterlogged soil profiles, where the groundwater system is near weathering bedrock. Acid groundwater is more likely to occur in soils developed from granite (soils contain pyrite, FeS_2) than from limestone or shales where soils contain carbonates (Ball 2003). Existing and historical wetlands contain iron sulfide minerals, which were formed under waterlogged conditions when there was no oxygen available to allow sulfides to decompose. These soils can be exposed to air through excavation in mining or urban development, drainage, stockpiling or through lowering of the groundwater table (WRC 2002).

Data collected in 1987 (George, unpublished) indicates that ferrolysis is the most likely process causing low pH in most wheatbelt groundwaters. Ferrolysis is the oxidation and hydrolysis of dissolved Fe^{2+} (Mann 1983), which has been attributed to the acidification of groundwater at playa margin discharge zones in the eastern wheatbelt (McArthur *et al.* 1991, Gray 2001). The process typically leads to the precipitation of red/brown insoluble iron oxides at the soil surface. In western wheatbelt areas, groundwater becomes enriched in ferrous iron with close proximity to mafic dykes, resulting in acidity via ferrolysis upon discharge at the ground surface.

Extent

Acid groundwater (pH < 4) has been found to be common in the WA wheatbelt (Mulcahy 1967; Mazor and George 1992), being present in around 20 per cent of bores monitored in the Central Agricultural Region (CAR). Investigations concerning the extent in the NAR are underway, with pH to be measured in about 200 bores. Preliminary results from initial surveys, along with informal reports from landholders, have indicated the presence of acid groundwater in some areas. However, until all of the bores have been measured for pH, it is not possible to quantify the extent or severity of acid groundwater in the NAR, or be confident about the possible factors contributing to its occurrence. Outlined below are the findings of the CAR in relation to the monitoring of acid groundwater.

The extent to which the acid generating transformation of sulfides (primary or secondary) to sulfate occurs in the eastern and western wheatbelt of the CAR is minimal, and this process may not have contributed to acid generation in recent geological times. This conclusion was reached after analysing geochemical data, which determined that chloride (Cl) to sulfate (SO_4) molar ratios of groundwater is often greater than 25. This figure contrasts with the $Cl:SO_4$ ratios of both rainfall and groundwater subjected to previous sulfide oxidation, respectively, 7 and less than 2. This latter figure suggests an additional source of sulfate from previous sulfide oxidation (WRC and DEP 2002).

In the CAR, acid groundwater in the eastern wheatbelt, distant from salt lake environments and/or too deep for active ferrolysis to be occurring has also been identified. The presence of this acidity may be explained though one or a combination of the following:

1. density driven reflux of acidified brines, with acidity possibly maintained due to the exhaustion of buffering agents in the immediate vicinity;

2. acid diffusion in groundwater, from higher concentrations near playas to relatively lower concentrations remote from playas; or

3. residual acidity from rock weathering that has been preserved within valley groundwater systems. This style of acid generation would be analogous to the process currently

occurring in the western wheatbelt, and also explains why some catchments have acid groundwater while other nearby catchments do not.

Impacts

Encroachment of acid saline water to the near surface environment is a consequence of rising watertables, whether drainage occurs or not. Seeps in the western wheatbelt discharge acid and brackish-saline 'baseflow', though net loads are arguably no different, whether they are artificially drained or not. These western seeps have been water accumulating locations and impacts of acidity have become more apparent following clearing and seep expansion. However, increasing volumes of acid water seepage may impact streams, ecosystems and soils, both on- and off-site. In the eastern wheatbelt, diffuse source seepage of acid groundwater is increased considerably by drainage and pumping, although flows and loads can be modified using containment strategies.

Corrosive acid groundwater can damage ecosystems and infrastructure, depending on concentration and the time over which the water remains unbuffered. Acid groundwater is typically saline to hypersaline, and may also contain ions (e.g. aluminium, lead, copper, cadmium, manganese and other heavy metals and radionuclides) that could pose a public health or environmental threat. Impacts related to poorly managed discharge of acid groundwater may become more apparent as the adoption of groundwater drainage and pumping practices increases.

Some of the impacts are outlined below:

- Disposal difficulties arise when handling the affected groundwater unless acidity is neutralised or reduced. Naturally formed acid water bodies are known to exist throughout the wheatbelt and local ecosystems have adapted to those conditions over time. Those ecosystems not adapted to such conditions, and with a retained conservation value, are at risk of degradation through improper disposal of acid groundwater.

- On-site/off-site seepage of acid groundwater may cause pH shifts in stream ecosystems and irreversible changes in subsoils, potentially affecting production systems.

- Productive uses are limited when alternative industry looks to use acid groundwater due to its pH (e.g. death of fish in aquaculture). Presence of heavy metals and bioaccumulation of contaminants also affect end use.

- Detrimental to built infrastructure: metal and some synthetic components used in pumps and desalination equipment are likely to degrade more quickly when exposed to water that is acid. Concrete life expectancy is also reduced (e.g. culverts).

Management options

Effective management of acid groundwater first requires it to be characterised in order to develop a chemical treatment with sufficient neutralising capacity. Treatment systems are dependent on both flow and load (e.g. acid, metals, salts, etc.). Some forms of acid treatment are less effective when large amounts of iron and aluminium are present, as is often the case in the wheatbelt. Information regarding management of large volumes of acid groundwater is still being developed.

1. Chemical adjustment of pH (Recover)

Limestone, hydrated lime, sodium hydroxide, sodium carbonate, or ammonia can be used to treat acid groundwater. There are many advantages and disadvantages of using different chemicals to adjust pH including, cost, reaction time, effectiveness, and handling dangers. Residues from chemical treatment such as ‘red mud’ from bauxite processing are an example of by-products that need to be disposed of properly. *Limestone channels and anoxic drains* can be used where acid groundwater must be conveyed over some distance prior to or during treatment. These management options generate only small amounts of alkalinity. *Anaerobic wetlands* have organic-rich substrates which exchange dissolved metals. This exchange occurs between the dissolved metals and abundant humic and fulvic acids contained within the substrate (Wildeman *et al.* 1991). Soluble metals are converted to insoluble forms by the anoxic conditions of wetland sediments (Fennessy and Mitsch 1989). Settling of suspended solids occurs from water velocity control by wetland vegetation (Brooks 1984).

2. Physical barriers (Contain)

Isolation from environmentally sensitive areas is another way of handling acid groundwater. Good engineering, construction practices and site investigations need to be performed when deciding on such management. A breach of barriers due to degradation of materials or due to climatic extremes is a risk.

Effectiveness

Information for treating acid discharges is derived mainly from reported information on acid mine drainage. Virtually no information exists for the treatment of natural acid groundwater in the quantities potentially present in the NAR. Combinations of management options are common in the treatment of highly acid effluents. The limitations of effectiveness in acid mine drainage treatment are also likely to apply to acid groundwater.

1. Chemical adjustment of pH

Downstream effects and disposal of residues created during chemical treatment must be considered. Chemical treatment options are on going and continuous chemical supply is required for the life of the project. *Limestone channels and anoxic drains* can become clogged with metal hydroxides due to oxidation and pH increases. Provided water flows fast enough, the abrasive action of the water can dislodge these coatings maintaining some neutralising effects. Addition of limestone to existing deep drains used for salinity reclamation may render them ineffective due to blockage. Water flow velocities in deep drains are too low to maintain an abrasive action on large limestone particles. *Anaerobic wetlands*: these have proved capable of removing iron and producing alkalinity. The primary factor limiting their effectiveness is the slow mixing of the alkaline substrate water with acid waters near the surface. This slow mixing can be overcome by constructing very large wetlands to provide long retention times (Skousen 1997). This demand on land area is a major impediment to the increased use of this option.

2. Physical

Barriers only hold acid groundwater and do not produce alkalinity without the addition of neutralising agents. The corrosive properties of detained acid groundwater need to be monitored and tested when evaporation is used to reduce volumes. Care is required when volume reduction via evaporation takes place to prevent accumulation of excessive concentrations of contaminants.

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ISSUE 2: ACID SULFATE SOILS

Cause

Acid sulfate soils (ASS) have generally been formed from inundation of sediments by seawater containing sulfate. As most sediments contain iron oxides and organic matter, sulfate from seawater reacts to produce iron sulfate in waterlogged conditions or iron sulfide (FeS_2), commonly known as pyrite. Through a combination of chemical and microbiological processes, pyrite or iron sulfate reacts with oxygen when the soil drains to form sulphuric acid, as shown below (Moore *et al.* 1998).

$$4\ FeS_2 + 15\ O_2 + 2\ H_2O \rightarrow 2\ Fe_2(SO_4)_3 + 2\ H_2SO_4$$

Extent

Potential acid sulfate soil is the common name given to soil and sediment containing iron sulfide. These can develop into actual acid sulfate soils if they become exposed to air. The extent of existing and potential acid sulfate soils in the NAR, and Western Australia generally, is currently very poorly understood and urgently requires investigation.

While acid sulfate soils are usually associated with estuarine deposits, highly acid sulphate materials have also been identified in swamps on the Swan Coastal Plain in Perth and underneath the Scott Coastal Plain. In addition to this, it has recently been recognised in South Australia that extensive inland areas featuring saline soils may also be at risk of acid sulfate soils where deep upwellings of saline, sulphate-rich regional groundwater reach the surface (Fitzpatrick *et al.* 2000). Research into the likelihood of this problem occurring in Western Australia is being undertaken (S. Wong, pers. comm.).

Impacts

Acid sulfate soil only becomes a problem if it is exposed to the air. Disturbance or drainage of these susceptible soils can lead to (Ahern *et al.* 1998):

- toxic quantities of acid, aluminium, iron and heavy metals contaminating land and adjacent waterways;
- contamination of groundwater with arsenic and heavy metals;
- soil structure decline and increased water erosion risk;
- reduced plant productivity;
- detrimental effects on the health of animals and humans associated with the consumption of aluminium rich water;
- severe impacts on aquatic flora and fauna and riparian vegetation; and
- infrastructure will also be seriously affected, including pipes, foundations and road surfaces susceptible to corrosion, which leads to accelerated structural failure.

Management options

The key management option is to recognise the existence of potential acid sulfate soils and **contain** the problem by avoiding land disturbance. Field identification of potential acid sulfate soils is possible using various soil, water and vegetation indicators (Dairy Industry Development Company 2001). Management depends on the existing quantities of sulfide mineral, acid loads produced and the area under threat. Options include:

1. Efficient water and drainage management systems.
2. Careful selection of pasture species and effective pasture management.
3. Fencing off affected areas and rehabilitation.
4. Revegetating groundwater recharge areas and utilising perennial pastures.
5. Establishing tolerant species in scalds to stabilise soil and prevent erosion and acid run-off when it rains.
6. Treatment of affected land or drainage water (within channels and ponds) using liming and aeration techniques (where economical).

Effectiveness

Site specific management options for acid sulfate soils described above have been effective in other States of Australia, but are largely untested under Western Australian conditions. The underlying management principles described, however, should be transferable.

1. Effective watertable management (preventing oxidation) has been the key to the efficient management of acid sulfate soil. Wherever possible, these soils should not be drained, and avoiding disturbance is always the preferred management option. If drainage is necessary, then broad shallow drains should be used to prevent disturbance of potential acid sulfate soils. Deep drains should not be used in areas with acid sulfate soils.
2. Highly productive pastures have been established on land influenced by acid sulfate soil, due to careful species selection and management to match the soil conditions.
3. Fencing off and rehabilitating affected land can be successful in small areas. Larger scalds are quite difficult to manage.
4. Revegetation with perennials in recharge areas has lowered watertables.
5. Careful species selection has helped to stabilise affected areas, reducing erosion and acid run-off.
6. Liming and aeration may be an uneconomical practice on a broad scale, but on a small area, may be effective to neutralise sulphuric acid in soil or water.

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ISSUE 3: BIOSECURITY

Cause

The presence of plant and animal pests and diseases in Western Australia is the result of deliberate or accidental introductions since settlement, or incursions from other States and Territories. Biosecurity is a general description for a set of measures designed to protect the land from the entry and/or impact of harmful pests, diseases, weeds and unwanted animals.

In Western Australia the focus of biosecurity is on threats that impact agricultural market access, production efficiency, sustainability, environmental protection, product safety and public health. The emphasis at the Department of Agriculture is on identifying and managing threats that are likely to have the greatest impact on agriculture and the related environment (DAWA 2003a, unpublished).

Extent

All subregions in the NAR are affected by introduced animal and plant pests that impact upon agricultural production and the environmental value of wetlands, woodlands and remnant vegetation. Plant diseases, such as rust and anthracnose, which affect the productivity of agricultural crops are common. However, animal diseases in the NAR are uncommon, with footrot the only significant disease previously detected. Primary producers do however, need to remain vigilant against such diseases as Johne's, tuberculosis and brucellosis.

The Department of Agriculture has prioritised plant and animal pests and diseases in order of their economic impact on agricultural production. Accordingly, biosecurity risks in WA from highest to lowest priority are diseases, invertebrate pests, weeds pests and animal pests. However, community consultation has indicated that plant pests, feral animals and disease introduction are the highest priorities for action.

It is anticipated that a Regional Biosecurity Plan will be developed in the near future that will identify the key threats to industry and the environment, as well as strategies to manage these threats. Table 3.1 shows the occurrence of plant and animal pests in the NAR.

Table 3.1: Plant, animal and disease risks managed by Biosecurity at subregional level

Risk	Impact	Greenough	Yarra Yarra	West Midlands	Moore River
Animal					
Deer	Enviro/Production	Y		Y	Y
Emus	Production	Y	Y	Y	Y
Exotic birds	Enviro/Production	Incident reports only (sulphur-crested cockatoo, sparrows) to have an impact when numbers increase and population expands into the region)			
Foxes	Predatory /Enviro on corridors	Y	Y	Y	Y
Native parrots	Enviro/Production	Y	Y	Y	Y
Pigs	Enviro/Production	Y	Y	Y	Y
Rabbits	Enviro/Production	Y	Y	Y	Y
Wild dogs	Predatory	Y	Y		Y

Risk	Impact	Greenough	Yarra Yarra	West Midlands	Moore River
Plants					
Acacias (introduced)	Environmental	Y	Y	Y	Y
African thistle	Enviro/Production	Y	Y	Y	Y
Apple of sodom	Enviro/Production	Y	Y	Y	Y
Arum lily	Enviro/Production			Y	Y
Bridal creeper (WON)	Environmental impact	Y	Y	Y	Y
Cape tulip	Enviro/Production	Y	Y	Y	Y
Cotton bush	Enviro/Production	Y	Y	Y	Y
Geraldton carnation weed	Environmental	Y	Y	Y	Y
Golden dodder	Production	Y			
Heliotrope	Production	Y	Y	Y	Y
Introduced grasses	Enviro/Production	Y	Y	Y	Y
Paterson’s curse	Production	Y	Y	Y	Y
Saffron thistle	Enviro/Production	Y	Y	Y	Y
Skeleton weed	Production	Y	Y	Y	Y
Tagasaste	Enviro/Production	Y	Y	Y	Y
Thornapple	Enviro/Production	Y	Y		Y
Variegated thistle	Production	Y	Y	Y	Y
Watsonia/African cornflag/	Environmental	Y	Y	Y	Y
Disease					
Soil-borne diseases	Stock and potentially native fauna	Stock movement intra- and inter-region			
Plant diseases, e.g. rusts	Production	Machinery and people movement intra- and inter-region			
Intensive feedlots, piggeries	Stock and environment	Site specific			
Plant pests					
Insect pests	Production	Monitoring/surveillance occurs across the region, e.g. pheromone trapping for *Trogoderma variabile* (warehouse beetle)			
Red imported fire ants	Enviro/Production	Monitoring/surveillance occurs across the region			
Asian gypsy moth	Enviro/Production	Monitoring/surveillance occurs across the region			
Queensland fruit fly	Enviro/Production	Monitoring/surveillance occurs in susceptible areas of the region			
Australian plague locust	Enviro/Production	Monitoring/surveillance occurs across the region			

Impacts

Agricultural and environmental pests create significant problems for landholders and managers in the NAR. Introduced plant pests compete with native species and/or agricultural crops and pastures, with the cost to agricultural industries being estimated at about $3.3 billion per annum nationwide (ARMCANZ, ANZECC and Forestry Ministers 1997).

In WA's agricultural systems, weed control costs have been estimated at 20 per cent of production costs and can be significantly higher in some instances (Department of Agriculture 2001). Weed invasion is regarded as a severe threat to natural ecosystems, but cost is difficult to measure in monetary terms.

Introduced and native animal pests damage native vegetation, agricultural crops and landscapes, and compete with or kill native animals and stock. Rabbits and foxes are two of the most common vertebrate pests in the NAR. Other vertebrate pests include rodents, deer, feral pigs and goats, and native parrots and cockatoos. Invertebrate pests, such as diamond back moths, grain weevils and heliothis have previously had significant impacts on crops in the NAR. Plant diseases also primarily impact production. Issues such as increasing incursions of new wheat rust strains require production research and management, but do not generally have broader environmental impact. These risks may present systems issues and changes in management practices to address such issues may in turn impact on other agricultural management processes (Department of Agriculture 2003a, unpublished).

Management options

Currently the management of introduced animal and plant pests is the responsibility of the landholder. The Department of Agriculture provides landholders with options for the control of these pests through Farmnotes, advice and risk assessments.

Coordinated community control programs are seen as the most effective and cost efficient method of reducing animal pests and the establishment of local weed groups will benefit communities and assist in the management of plant pests.

Control methods used for introduced animals such as feral pigs, rabbits and foxes include trapping, poisoning, shooting, exclusion and to a small extent biological control through myxomatosis and rabbit haemorrhagic disease (RHD). Plant pest management is either carried out through mechanical or chemical control, however, biological control agents are beginning to play an important part in the management of some plant pests.

It is important for landholders to adopt good biosecurity measures for their properties. By having a good biosecurity plan, landholders can reduce significantly the possible introduction of an unwanted pest or disease (Department of Agriculture 2003b).

Various biosecurity control legislation, practices and programs are in place to manage biosecurity risks, including:

- State legislation and policies on weeds and animal pests, such as the *Agriculture and Related Resources Protection Act 1976* which provide wide powers for the detection and eradication of pests.
- Quarantine programs at State borders, ports and airports.
- Incident management carried by the Department of Agriculture for incursions or outbreaks of exotic animals and plant pests and diseases affecting agriculture.
- Industry program designed to development risk management plans, and detect and eradicate pests, such as 'GrainGuard', 'BeeGuard' and 'StockGuard'.
- Eradication programs for vertebrate and invertebrate pests.
- Animal health programs targeting eradication, control or management of serious animal diseases.
- Provision of research, advice and risk management and coordination in relation to animal and plant pests.

- Small landholder training and farm planning support to inform the public about, and address, biosecurity risks.

Landholders are required by legislation to manage 'declared' plants and animals on their individual properties and have a range of chemical, physical and biological options available. The extent and effectiveness of landholders' control of declared and non-declared pests and diseases on their properties is dependent on the resources they have available and how seriously they regard the threat to be towards their productivity and natural resources. Community groups also have a range of options available to manage plant and animal pests; however they often lack the resources available for effective management.

Effectiveness

Total eradication of pest species is an unrealistic goal. Rather identification and prioritisation of significant threats to agricultural production and the environment, so that investment in control measures can be targeted effectively, is the key. The effectiveness of biosecurity programs and initiatives are also reliant on the accuracy of threat analyses, the resources available and the responsiveness of the landholders and community involved.

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ISSUE 4: CLIMATE CHANGE

Cause

Most of the past episodes of climate change during the history of the Earth have been attributed to variations in Earth's orbital characteristics, atmospheric CO_2 variations, volcanic eruptions and fluctuations in solar output. The current situation with climate change however, is considered to be largely due to increased CO_2 levels resulting from human activity since the Industrial Revolution in the early 1700s (Physical Geography.net 2004).

Human activity over the past two centuries has resulted in a significant increase in the amount of greenhouse gases in the atmosphere. Most greenhouse gas emissions result from fossil fuel use, ruminant digestion and land clearing. Approximately three quarters of anthropogenic atmospheric CO_2 increase over the past 20 years is due to fossil fuel burning, with the remainder due mainly to land-use change, particularly clearing. Slightly over half of the increases of methane (CH_4) is due to burning of fossil fuels, ruminant digestion, agriculture and landfills (Pittock 2003). Fertiliser application, waste decomposition and industrial processes are also significant contributors (Western Australian Greenhouse Taskforce 2003). CO_2, (CH_4) and nitrous oxide (N_2O) absorb outgoing long-wave infrared radiation, which keeps the earth warm. Increased concentrations of greenhouse gases have enhanced the earth's natural greenhouse effect, leading to higher average air temperatures in the lower atmosphere, and contributing to rising sea levels and altered rainfall patterns (Indian Ocean Climate Initiative 2002).

Climate variability across the south-west of Western Australia is also related to the Southern Oscillation Index (SOI) and Indian Ocean Sea Surface Temperatures (SSTs). The Southern Oscillation has some influence on atmospheric pressures across the Australian region. Strong correlations between surface atmospheric pressure and May-July rainfall are evident particularly in the South West Region. Conversely, the direct relationship between rainfall and SOI in the south-west, is weakly correlated. Rainfall decreases since the mid 1970s partly reflects large scale changes in the El Nino - Southern Oscillation. However, little change in the SOI in recent decades cannot reflect the additional decreases in rainfall, suggesting other unknown factors are also responsible. Indian Ocean SSTs appear to be correlated with south-west rainfall, with warm temperatures usually being associated with dry conditions. Both warming of the Indian Ocean and declining rainfall in the past few decades only show trends, but do not suggest any physical or causal link between these trends (Indian Ocean Climate Initiative 2002).

Therefore, it should be noted that while decreased rainfall and associated atmospheric circulation changes resemble the climatic changes most climatic models project for an enhanced greenhouse effect; this has not been proved beyond reasonable doubt and may simply reflect natural climatic variability. However, it is likely that both natural variability and the enhanced greenhouse effect have contributed to climate change (Indian Ocean Climate Initiative 2002). Further research to more accurately quantify the causes and implications of climate change should be a high priority.

Extent

Greenhouse has become a pre-eminent global sustainability issue (Government of Western Australia 2003). Atmospheric carbon dioxide (CO_2) concentrations have increased by 31 per cent, methane (CH_4) concentrations by 151 per cent and nitrous oxide (N_2O) has increased by 17 per cent since 1750. Continental interiors and the Northern Hemisphere are projected to experience greater warming trends, as well as the eastern tropical Pacific Ocean (but to a lesser extent). Warming of the eastern tropical Pacific Ocean leads to a more El-Nino-like state (Pittock 2003). When the SOI is strongly negative (El-Nino event), rainfall over most of

Australia, including the south-west of Western Australia are generally lower than normal. However, improved estimates through modelling of natural variability of the south-west climate could determine how much of the recent dryness and future drying conditions can be attributed to natural variability or enhanced greenhouse effect (Indian Ocean Climate Initiative 2002).

Australia emits about 1 per cent of global emissions, a small proportion of the total, but very large on a per capita basis. Western Australia emits approximately 12 per cent of Australia's total emissions. In 1999 WA's inventory of emissions on a sector basis revealed that the energy sector (stationary energy, electricity generation and transport) was the State's biggest greenhouse gas contributor (70 per cent of gross emissions), followed by agriculture (26 per cent of gross emissions). WA's net greenhouse gas emissions increased by approximately 5 per cent between 1990 to 1999. However, if land use change, forestry emissions and sequestration were excluded from the inventory, the increase was about 27 per cent (Western Australian Greenhouse Taskforce 2003).

CSIRO has simulated climate patterns under enhanced greenhouse conditions using global climate models and has developed some projections for WA. In general, WA is expected to become warmer and drier (particularly in the south) than at present. Over most of Australia, average annual temperatures are expected to rise by 0.4-2.0 degrees Celsius by 2030 and 1-6 degrees by 2070. Slightly less warming is expected to occur in coastal areas. Warming is likely to be greatest in spring and least in winter, affecting both daily maximum and minimum temperatures. Autumn and winter rainfall is expected to decline by as much as 20 per cent (relative to 1990 values) over the south-west and southern WA. Evaporation rates are expected to increase with temperature (Foster 2002). There are also projected increases in tropical cyclone intensity and possible changes in their location-specific frequency (Pittock 2003).

Impacts

Climate change scenarios include increased variability in weather, and increased frequency and intensity of extreme weather events. Farming systems will be further challenged by projected stresses such as increased drought frequency and severity, increased evaporation and shorter growing seasons. Farmers may have to consider switching to shorter growing season cereal and oilseed crop varieties than they are currently growing. It is projected that various regions in the NAR will be influenced differently by climate change; with the low rainfall zones potentially the most adversely affected, and areas in the high rainfall zone that are prone to waterlogging potentially benefiting from the drier conditions (I. Foster, pers. comm.).

Reduced rainfall and higher evaporation would suggest that the spread of salinity may decrease in the future; however daily rainfall events are predicted to be more intense and this may lead to increased episodic recharge, as well as water erosion. Overall drier conditions and shorter growing seasons may also increase the incidence of wind erosion (Foster 2002; Pittock 2003). Actions to reduce emissions from agriculture may influence tillage, fuel consumption, fertiliser application, burning and livestock practices (Western Australian Greenhouse Taskforce 2003).

It is possible that risk from insect pests and weed competition will also increase. Tree crops are particularly sensitive to temperature changes due to their long lead times for establishment and development, and those crops growing at the warm margin of their climatic range will face reduced hours of chilling and increased heat stress (Foster 2002; Pittock 2003).

The impact on native vegetation and remnant ecosystems will vary; however it is possible that the extinction of many species that have a restricted range or are confined to small areas may occur (Foster 2002). Increased incidence of bush fires may also threaten terrestrial ecosystems. Other ecosystems that are particularly threatened by climate change include coral reefs, and freshwater wetlands in coastal and inland areas. Coral reefs are sensitive to increased atmospheric carbon dioxide (decreases calcification rates of coral), rising water temperatures (coral bleaching) and cyclones/storms. There is insufficient information about the impacts of climate change on fisheries, but changes in winds, currents, water temperature and nutrient levels, as well as coral health are likely to have negative influences (Pittock 2003).

Changes in cyclone intensity and frequency, along with sea level rise, could have strong implications for coastal communities and infrastructure. The low-lying Abrolhos islands could be particularly vulnerable. Reductions and/or restrictions in agricultural, fisheries and industry output, along with increased insurance premiums, could have negative implications for local and regional communities and economies. Impacts of climate change on terrestrial and aquatic ecosystems could also have strong ramifications for tourism and community amenity (Pittock 2003).

Management options

- *Biofuels and alternative energy sources (Contain and Adapt):* Biofuels offer Western Australia an opportunity to reduce its greenhouse emissions, as they produce fewer greenhouse gases. It is estimated that biodiesel produces 75 per cent less accountable greenhouse emissions than diesel. Biofuels are generated from plant matter, such as residues from wood processing [i.e. Western Power's Integrated Wood Processing demonstration plant in Narrogin (http://www.oilmallee.com.au/imp.html)], canola oil and crop stubble.

- *Agro-forestry and carbon-sinks/trading (Contain and Adapt):* Commercial opportunities identified in the zone, along with medium and low rainfall zones, include broombush, oil mallees and sandalwood. Furthermore, these plants, as well as other salt tolerant species, may provide a source of revenue through carbon trading by acting as carbon sinks (Department of Agriculture 2003a; Kingwell 2003; Department of Agriculture 2003b).

- *New crop and pasture varieties (Adapt):* With the low rainfall zones in the NAR potentially the most adversely affected by climate change, these areas should consider switching to short growing season cereal and oilseed crop varieties, and low rainfall pasture varieties. Modern selection and breeding techniques are resulting in continual improvements in the genetic qualities of crop and pasture varieties that are more suitable to particular agronomic circumstances (Department of Agriculture, unpublished).

- *Inland aquaculture (Adapt):* Due to potentially adverse conditions developing in the marine environment as a result of climate change, it is possible that aquaculture ventures may be relocated to the mainland where conditions can be greater controlled. There is some potential for aquaculture ponds using saline groundwater, including finfish, algae and brine shrimp. Freshwater species such as yabbies, marron and silver perch have also been successfully produced commercially (Kingwell 2003; Agriculture Western Australia 2000).

- *Climate forecasting and decision support tools (Adapt):* Climate variability is a significant issue for farming and pastoralism. Good management of climate risks is vital for making a profit and remaining in business. Developments in climate forecasting abilities along with a number of climate related decision support tools, such as Australian Rainman and Potential Yield Calculator, provide information to landholders that enable them to adjust their farming practices and inputs according to how their season is tracking (Department of Agriculture 2004).

Effectiveness

- *Biofuels and alternative energy sources:* The Midwest area is regarded as being an ideal site for a biodiesel industry due to the availability of natural gas, transport infrastructure, industrial land and canola supplies. The main limiting point for the development of this industry relates to Excise Legislation and Regulation reform, along with industry investment (Department of Agriculture 2003a; Midwest Development Commission, n.d.).
- *Agro-forestry and carbon-sinks/trading:* It is likely both commercial and carbon sink plantings would need to reach critical masses before being able to support new industry development, and this may be more readily achieved by cooperative or joint venture arrangements that pool resources. Furthermore, it is unlikely that growing trees purely for the purpose of carbon sequestration is likely to be economically viable (at least under current and projected market conditions) and adjunct uses such as wood, pulp and bioenergy would be needed to supplement this activity. Nevertheless, there are a number of socio-economic benefits that could potentially flow from carbon-sinks, including improved land and water conservation, along with enhanced recreational, aesthetic and habitat values (CRC Greenhouse Accounting 2003).
- *New crop and pasture varieties:* Greater yields, quality, disease and pest resistance, soil condition tolerance and better agronomic suitability allows greater flexibility in cropping regimes, higher stocking rates and better risk management. Awareness, availability and price of new seed can limit the uptake of new varieties (Department of Agriculture, unpublished).
- *Inland aquaculture:* This industry is labour intensive, requires specialised technical knowledge, with capital and operating costs, and distance to market issues possibly being prohibitive (Kingwell 2003; Agriculture Western Australia 2003b). There must also be a plentiful supply of non-polluted water (A. Seymour, pers. comm.).
- *Climate forecasting and decision support tools:* Landholder familiarity with, and confidence in, these technologies and tools currently limits their utilisation. They are not intended for use by farmers and thus are not user-friendly. It is important that the outputs and interpretation can be applied by farmers (Department of Agriculture 2004).

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ISSUE 5: DRYLAND SALINITY

Cause

Natural, or 'primary salinity' occurs throughout the world in arid climates, including about 29 million hectares in Australia: 14 million hectares as salt marshes, salt lakes and salt flats, and another 15 million hectares with naturally saline subsoil but no groundwater or perched water to take it to the surface. Moist and wet primary saline areas have very high natural diversity in Western Australia, but are at risk from increased flooding.

Salinity which has developed by changing land use and management is called secondary salinity. The fundamental cause of secondary salinity is the replacement of deep-rooted perennial native vegetation with shallow-rooted annual crops and pastures used in agriculture. Salt in sea spray, mainly sodium chloride, is carried inland by prevailing winds and deposited by rainfall on the land in small amounts. This ranges from approximately 200 kg/ha/year near the coast, to 20 kg/ha/year on the eastern fringes of the agricultural areas.

In its natural state, native vegetation used most of the rainfall leaving the salts behind lower in the soil profile. Over thousands of years this has resulted in an accumulation of salt in the soil averaging approximately 1000 tonnes under each hectare of typical farmland. In higher rainfall areas (generally with well drained soils) salt store is lower due to leaching. In lower rainfall areas however, particularly those that are generally flat and poorly drained, salt store is high.

Agricultural crops and pastures that were planted after clearing used less water than the native vegetation they replaced. This has resulted in increased run-off and greater percolation of water beyond the root zone. This water accumulates as groundwater and causes the groundwater to rise. Once rising water levels are within one or two metres of the surface, evaporation of the water occurs and there is an accumulation of salt at the soil surface and in the root zone. This salt may emerge as a ‘saline seep’, or where a flat, bare area of naturally saline clay subsoil is exposed by erosion, evaporation at the surface leaves behind concentrated salt deposits known as ‘saline scalds’ (Nulsen and McConnell 2003).

Extent

Western Australia has the largest area of dryland salinity in Australia and the highest risk of increased salinity in the next 50 years (Land and Water Australia 2000). The NLWRA states that an estimated 4.3 million hectares (16 per cent) of the south-west currently has a high potential of developing salinity from shallow watertables. This is predicted to rise to 8.8 million hectares (33 per cent) by 2050.

The Land Monitor Project delivered a number of map products relating to the current area of salinity and the area considered to be at risk of salinity in the future. The current area of salinity was mapped as ’areas of consistently low production’ (AOCLP). The areas considered to be at risk of salinity in the future were constrained to the lowest areas in the landscape and were derived by determining for a particular point its ‘average height above valley floor’ (AHAVF). Table 5.1 presents Land Monitor Project data for each of the NACC subregions. The area of each subregion covered by the Land Monitor Project is variable because the project was confined to the cleared agricultural area and two of the NACC subregions extend into the pastoral area.

Table 5.1: Land Monitor Project data for the four NACC subregions

NACC subregion	Total subregion area	AOCLP (excluding remnant vegetation)	AHAVF (at risk)
West Midlands	1,143,173 ha	10,471 ha (1%)	255,283 ha (22%)
Yarra Yarra	1,791,584 ha	73,563 ha (4%)	332,785 ha (19%)
Greenough	3,415,820 ha	36,557 ha (1%)	308,571 ha (9%)
Moore River	1,598,948 ha	175,632 ha (11%)	482,662 ha (30%)
Totals	**7,949,525 ha**	**296,223 ha (4%)**	**1,379,301 ha (17%)**

In the northern agricultural region, most of the current extent of dryland salinity occurs on the Yilgarn Craton. The Yilgarn Craton underlies most of the Yarra Yarra subregion and parts of the Moore River and Greenough subregions. The amount of land affected by salinity is about 10 per cent of the area. It is predicted this could expand to about 25 per cent of the area. While significant, this only represents a doubling of the area affected by salinity compared to a potential twentyfold increase predicted for the Perth Basin (see below).

The entire West Midlands subregion and parts of the Moore River and Greenough subregions overlie the Perth Basin. Groundwater levels are observed to be rising at higher rates and more consistently in the Perth Basin compared to any other geological area in the northern agricultural region. It is within the parts of the subregions overlying the Perth Basin that there is likely to be the greatest increases in the area of dryland salinity. Presently the area of salinity is relatively small (~ 1 per cent) but potentially could expand to affect about 20 per cent of the area.

Parts of the Yarra Yarra, Greenough and West Midlands subregions overlie the Irwin Sub-Basin. Groundwater in the Irwin Sub-Basin is typically saline and little utilised. Consequently, knowledge of groundwater processes and trends is poor. Much of this area is characterised by flat to gently rolling plains cut by deeply incised drainage lines. It is likely that these drainage lines play a crucial role in draining saline groundwater possibly limiting watertable rise and salinity developing. If this is so, then maintaining the health and integrity of these drainage lines is imperative (Speed 1991).

The Northampton Block, which is situated entirely in the Greenough subregion is considered to have a moderate salinity risk with medium salt storage. Large parts of this area appear to be approaching or may have already attained hydrological equilibrium. That is, groundwater levels rise and fall in response to seasonal conditions, but the longer term trend is stable, particularly in the southern portion around the Chapman Valley. However, the severity of salinity can continue to develop in wet areas and seeps by evaporative concentration (Speed 2002).

Impacts

Secondary salinity following land clearing impacts greatly on the agricultural area of Western Australia. Large tracts of once productive land, especially in valley floors, have become saline, species richness has already declined and many of the south-west rivers are now too salty for irrigation or consumption (Moore 1998). Details of the impacts are outlined below:

- **Loss of productive agricultural land:** Salinity leads to the poor growth or death of plants, and salinity combined with waterlogging is most detrimental for plant growth. Of the 4.3 million hectares (16 per cent) of the south-west potentially at risk from shallow groundwater, 81 per cent is agricultural land. Predictions, based on current and perceived land uses, indicate that shallow watertables and salinity may affect approximately one-third of agricultural areas by 2050. (Land and Water Australia 2000).

Sodium ions, present in most salts, cause degradation of soil structures making them more susceptible to erosion and contribute to water run-off. Run-off of salty water is a contributor to stream salinity.

- **Loss of biodiversity** caused by the detrimental effects of secondary salinity on bushland remnants and wetlands. Twenty-one of the 54 wetlands located within the agricultural region are potentially at risk of shallow watertables, which may affect wetland health. In addition, an estimated 1500 plant species will be affected, with 450 possibly subject to extinction. The effects of salinity are likely to reduce fauna species by 30 per cent in affected areas, and terrestrial animals will decline significantly (e.g. a 50 per cent reduction in the number of water birds using wheatbelt wetlands is anticipated due to the salinity-induced death of shrubs and trees, with the onset of salinity) (Land and Water Australia 2000).
- **Reduction of available groundwater supplies** for stock consumption. With continued recharge and salt mobilisation, water bores are likely to begin drawing on expanding saline groundwater systems.
- **Detrimental effects on town sites and infrastructure:** Approximately 30,000 km of road and rail networks and up 30 rural towns may potentially be affected. Damage to buildings, recreation facilities and difficulties with public utilities including water supplies and waste management systems is also likely (Land and Water Australia 2000).
- **Increased risk of water erosion:** As denuded and waterlogged topsoil is more susceptible to detachment and transport (Tille *et al.* 2001).

Management options

The Department of Agriculture has prepared a draft Salinity Investment Framework (George and Kingwell 2003), which outlines the estimated extent of land salinity under different management scenarios. The framework includes the probability of adoption and technical feasibility of management scenarios for each soil-landscape zone. Effective management of secondary or dryland salinity includes managing both the catchment and salt affected areas (Moore 1998). Options for managing these are outlined below (summarised from Tille *et al.* 1991 and Moore 1998):

1. **Adopting low recharge farming systems:** To replace current agronomic practices with alternative, economically viable systems, that increase evapotranspiration and reduce the amount of water percolating below the root zone.

    - *Improve annual crop and pasture agronomy (Contain):* By looking at species and variety selection, fertiliser applications, weed control, and timing of treatments.
    - *Use of perennial plants (Contain):* Pastures which are capable of growing throughout the year, and trees or fodder shrubs, which combine the advantages of deep root systems and year round growth with higher water use, due to their large leaf area.
    - *Managing soils with major chemical and/or physical limitations (Contain and Adapt):* As they may create a severe productivity limit and are often also major recharge and/or erosion sites, particularly acid yellow sandy earths, pale deep sands, shallow gravels, rock outcrops and bedrock ‘highs’.
    - *Protect, manage and enhance the remnant vegetation (Contain and Adapt):* To maintain existing water use and contribute to reducing groundwater recharge.

2. **Engineering solutions:** Are required in addition to increasing water use by plants. These options help to prevent water from recharging and remove saline water from the catchment.

    - *Managing surface water (Recover and Contain):* Includes incorporating water harvesting, pumps, banks and drains into farm and catchment water management strategies.

    - *Managing groundwater (Recover and Contain):* To lower watertables, preventing continued accumulation of salts while allowing rainfall to leach salt from the upper soil profile. These techniques function by increasing the rate of discharge, and consequently reduce the area of groundwater discharge necessary to establish equilibrium. This often involves deep drains, pumps or siphons.

3. **Living with salinity:** To make productive use of land and water that is already salt affected.

    - *Saltland pastures and crops (Adapt):* Saltland plants can provide some production from what is otherwise generally unusable land.

    - *Aquaculture (Adapt and some recovery and containment through associated works):* There is some potential for aquaculture ponds using groundwater drainage from salt affected areas.

    - *Evaporation basins and salt harvesting:* Basins can be used to dispose of saline groundwater until it evaporates (JDA and Hauck 1999). *(Adapt and some recovery and containment through associated works):* Commercial harvesting of salt from an evaporation basin may be an option.

    - *Desalination (Adapt and some recovery and containment through associated works):* Converts saline or treated wastewater into fresh water of drinking quality (potable) and industrial use. Generally, distillation and reverse osmosis (RO) are used for seawater desalination, while RO and electrodialysis are used to desalinate brackish water (Department of Agriculture 2003).

    - *Mineral extraction (Adapt and some recovery and containment through associated works):* From saline water for use by industry, animal nutrition and as dust suppressants.

Effectiveness

'Salinity is a complex problem and the environmental and hydrological processes are highly varied. Each situation involving dryland salinity has its own peculiarities and there is no single, overall solution. Solutions will require a blend of approaches tailored to meet local conditions.' (Tille *et al.* 2001).

1. **Adopting low recharge farming systems**

    - *Improve annual crop and pasture agronomy:* There is only a limited potential for increasing the water use of conventional annual crops and pastures. Hall (2002) suggests that improving cereal agronomy to reach close to theoretical yield potentials will only increase the water use of an average crop by approximately 4 per cent. Mainly because increased biomass production and increased transpiration is largely offset by decreased evaporation from the soil surface. Selecting species or varieties matched to the environmental conditions and good management of fertilisers and grazing will all help extend the period of water use by annuals (Tille *et al.* 2001).

- *Use of perennial plants:* The main role of perennial species is to relieve hydraulic pressure by reducing recharge during summer/autumn and by creating a soil water buffer during this period, which helps to reduce recharge during winter. Perennials are most effective when used to manage salinity derived from local flow systems. Perennials do use more water than annual species in the late spring, summer and autumn, and the deeper-rooted perennials (trees) are the highest water users (Tille *et al.* 2001). Lucerne has been used as one of the main broadacre recharge management tool for the CAR. However, the applicability of the use of lucerne in the NAR is considered limited, due to difficulties in relation to establishment, plant survival and performance, and opportunity costs (D. Rogers, pers. comm.).

- *Managing soils with major chemical and/or physical limitations:* Any soil management, which achieves a reduction of waterlogging, will help combat salinity. Soil management that improves any chemical or physical restrictions to plant growth and improves crop water use by allowing greater root exploration and more thoroughly drying the soil profile, prior to the next season, may have substantial benefits (Tille *et al.* 2001).

- *Protect, manage and enhance the remnant vegetation:* Protecting and enhancing areas of native vegetation will contribute to overall water use as well as protecting wildlife habitat and biodiversity. Remnant vegetation kept in good condition will have a similar water use to the native vegetation before it was cleared (Moore 1998).

2. Engineering solutions

- *Managing surface water:* The severity and impact of salinity is diminished if waterlogging is reduced as a result of well designed and situated surface water management techniques, such as shallow drains and raised beds. It may also contribute to increasing total plant water use by improving the conditions for plant growth (Tille *et al.* 2001). Reduced waterlogging will also have a positive impact on recharge through enabling preferred pathway flow. A common theme amongst landholders is that public road crossing culvert flow capacity is generally too low, causing inundation and sedimentation, which further adds to waterlogging/salinity problems; however, only anecdotal evidence exists concerning this issue currently.

- *Managing groundwater:* Low permeability of materials on many salt affected areas can reduce the effectiveness of groundwater drainage. Effectiveness of these solutions is variable and careful site assessment and drain design are essential to increase the chances of success (Tille *et al.* 2001). Cost/benefit analysis is strongly recommended before implementation of such options.

3. Living with salinity

- *Saltland pastures and crops:* Successful revegetation of saline areas with salt and waterlogging tolerant species will increase water usage, and may help lower watertables (Tille *et al.* 2001). They are likely to be profitable across a range of scenarios, with the optimal area varying considerably according to site characteristics and market conditions (O'Connell and Young 2002). Waterlogging and saline soils often occur together, requiring some form of surface water management to maintain saltbush that is not tolerant to waterlogged conditions.

- *Aquaculture:* The use of saline water for aquaculture is well documented (e.g. in Tille *et al.* 2001), however operating costs and distance to market issues may be prohibitive, and there must be a plentiful supply of non-polluted water (A. Seymour, pers. comm.).

- *Evaporation basins and salt harvesting:* Storage of salt on site is considered the best option for evaporation basins. Commercial harvesting of salt from evaporation basins has only been successful in a few isolated cases, however, it is not usually a financially viable option for salt disposal unless a local niche market is identified (JDA and Hauck 1999).
- *Desalination:* Developing water resources from saline water is possible by using desalination technologies. However, desalination can be costly because it is energy intensive (Department of Agriculture 2003). The successful applicability of desalination is variable in each situation and may not be cost effective on a small scale (L. Hopgood, pers. comm.).

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ISSUE 6: FLOODING

Cause

Flooding is not to be confused with waterlogging. Flooding is stormwater flowing outside its usual channel, which may pond in flat areas (Moore and McFarlane 1998). It is dependent on rainfall intensity and is caused by accumulation of water downslope from rocky outcrops, roads, non-wetting soils and hardpans that shed water. Saturated soils cause run-off which increases the likelihood of flooding, most common in rainfall areas > 400 mm (Moore and McFarlane 1998). It also occurs over soils that appear saturated due to slow infiltration in duplex soils, where internal drainage reaches the clay subsoil causing the watertable to temporarily perch (Hunt and Gilkes 1992).

Extent

Flooding usually occurs along drainage lines, in low-lying valleys and on land with poorly defined drainage networks. The frequency of flooding is generally highest in high rainfall zones, although the impact upon these may not be the most significant. It can be split into local flooding, which is restricted to small catchments and regional flooding, where large areas are affected such as when major rivers break their banks. Since the mid-1960s Western Australia has been experiencing below-average annual rainfall and has had relatively little major flooding, especially in the south-west (Water and Rivers Commission 2000).

Rivers and drainage lines located in catchments that have been cleared for agriculture are more prone to flooding than those where the natural vegetation has been retained. Catchments where land is cultivated regularly have an even higher risk due to compaction and hardpan formation, allowing less infiltration. Catchments with increasing areas of salinity and waterlogging experience order of magnitude greater flood peaks because of the proportion of the catchment that remains saturated between rainfall events (Bowman and Ruprecht 2000). This was graphically illustrated in parts of the Moore River subregion in 1999 when extensive flooding was experienced.

There is no consistent mapping of the extent of flooding or flood prone areas across the agricultural regions. Individual flood events have been tracked by satellite imagery and the Water and Rivers Commission produces flood risk maps for heavily populated areas. Modelling has also been carried out in certain catchments. The following data is based on the flood hazard assigned to land units in the Department of Agriculture’s soil-landscape mapping.

Table 6.1: Flood hazard in the NAR (Department of Agriculture 2003a)

ZONE	Area of private agricultural land (ha)	Land with moderate to high risk of flood hazard[1]	
Subregion		ha	%
Greenough	1,776,237	50,469	2.84
West Midlands	742,584	16,585	2.23
Moore River	1,279,578	178,574	13.96
Yarra Yarra	921,222	104,407	11.33
TOTAL	**4,719,621**	**350,035**	**7.42**

[1] Land likely to be affected by moving floodwaters at least once in every ten years.

The above data is as much indicative of those landforms that contribute to the generation of flood events, in as much as they are affected by them. As mentioned above, an understanding of flood potential can only be determined from the tracking of actual events and modelling. This is mainly due to the large number of variables that contribute to flood generation, such as landscape formation, storm probabilities, land use and run-off generation. Even when flood events are recorded and tracked, there is often a general lack of locally recorded and accurately observed climatic and run-off data to provide information on the processes that occurred to generate such events.

Impacts

The impacts of flooding include: damage to infrastructure, interruption to communication and transport, crop and stock losses, erosion and consequently sedimentation. The impacts are summarised in Tille *et al.* (2001).

Management options

The agricultural areas of Western Australia are still undergoing immense hydrological change in response to clearing and development. Our understanding and ability to determine the potential impacts of this, as well as our ability to develop remedial measures, is greatly hindered by our lack of suitable climatic and landscape run-off information. To date, the State has invested poorly in the gauging of streams and catchments in other than those used for urban and irrigation water supplies. This limits our knowledge base and ability to model and predict run-off and flood events generated within all but about 10 per cent of the South West agricultural area.

Before we are able to make anything more than general statements on flood risk and the methods and economics of reducing these, we need to undertake stream gauging and related modelling on a far greater scale.

To date, our knowledge is based on common sense, supported by observation, which indicates that on a small scale the following tools (described in detail in Tille *et al.* 2001) may be effective:

1. **Lower recharge farming systems (Recover and Contain):** Which are also designed to combat salinity and waterlogging and may reduce the risk of flooding.

2. **Temporary detention (Contain):** Wherever possible by incorporating practices that are generally used to reduce soil erosion, e.g. grade banks and working land on the contour.

3. **Installation of earthworks and water harvesting schemes (Recover and Contain):** To regulate and reduce run-off from contributing landforms and catchment areas.

4. **Groundwater drainage schemes (Recover and Contain):** That de-water waterlogged areas between storm events to provide greater soil infiltration capacity.

On a regional scale options may include:

5. **The use of natural lakes and wetlands (Contain):** To act as detention basins to attenuate flood events.

6. **Regional scale drainage schemes (Recover and Contain):** That drain land and divert flood flows away from infrastructure to detention and disposal areas.

Effectiveness

1. **Lower recharge farming systems** have the potential to reduce run-off caused by saturation excess and may provide traps for silt, to help reduce the flow-on effects of silted culverts and water courses, etc.

2. **Temporary detention** is likely to be beneficial in small and moderate storm events. The benefits reduce during severe or prolonged storm events.

3. **Installation of earthworks** and water harvesting schemes is often a successful option on a local scale. These generally provide significant localised benefits and cause few off-site problems providing schemes are properly designed.

4. **The use of natural wetlands:** If properly managed the flow of water through these can provide benefits in terms of flood control, conservation and to the community. However, these projects would require expert input and formal approval.

5. **Regional scale drainage schemes:** Can provide significant benefit on the greater catchment scale, and alleviate community concerns regarding water and flood management. However, these are likely to require formal approval, need to be properly designed and may require management by a controlling body.

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ISSUE 7: HERBICIDE RESISTANCE

Cause

Over the past two decades there has been a significant increase in area cropped and crop yields. This has been made possible in part to the use of chemicals as the main method of weed control, with less reliance on tillage and grazing as weed control measures. The high selection pressure associated with repeated use of chemicals has resulted in several weed species evolving resistance to the main chemical groups (Pannell *et al.* 1999).

Herbicide resistance is not due to mutation brought about by use of herbicides. It is caused by the selection of natural mutation or small pre-existing population of resisting plants. The selection pressure is exerted by herbicides. Usually the majority of the weed population is susceptible to a particular herbicide and the majority is killed. However, a minority of the population may be less competitive and possibly exhibit natural resistance, which proliferate when given the opportunity. Continual use of herbicides leads to population changes, where susceptible biotypes decrease in numbers and resistant biotypes increase in numbers. Highly effective herbicides will screen the area, removing susceptible weeds, leaving resistant biotypes. Cross-resistance to herbicides may also occur when individuals develop resistance to herbicides with different modes of action (University of Minnesota Extension Service 1998).

Extent

Different weeds take differing amounts of time to build up resistance, with annual ryegrass (*Lolium rigidum*) being the most prone to developing resistance. Annual ryegrass is widespread in the region after being in the 1960s as a pasture plant. The NAR is regarded as having the worst herbicide resistant annual ryegrass problem in the world (P. Newman, pers. comm.). In the NAR, particularly on sandplain soils, there is strong reliance on the lupin:wheat rotation, with many paddocks cropped in this manner for as many as 25 years. The main means of weed control in this rotation has been by use of herbicides; this reliance on chemicals and lack of diversity in cropping systems has led to widespread herbicide resistance.

Impacts

Herbicide resistant weeds increase the cost of the farming system. Weeds that were once easy to kill with a selective herbicide must now be controlled through a range of Integrated Weed Management techniques, most of which are more expensive and time consuming than selective herbicides. In general, the sandplain soils of the NAR are the scene of the biggest herbicide resistance problem. The lupin:wheat rotation has been a big success story for this soil type over the past 20 years. Growers are faced with the dilemma of changing this very successful farming system to less profitable systems, perhaps ones that include non-crop phases.

As well as posing a significant economic cost, herbicide resistance may result in a return of some traditional farming practices that are known to have significant environmental impacts. The temptation to introduce conventional weed control methods such as full cultivation, stubble burning or increased grazing could significantly increase the incidence and extent of soil degradation issues such as erosion, compaction and structural decline.

Management options

The answer to the problem of herbicide resistance is diversity. That is, to develop a farming system with a range of crop and pasture options with diverse measures of weed control.

Historically, the common farming system in the NAR has been predominantly continuous cropping (e.g. lupin:wheat rotation) with a reliance on herbicides for weed control. What is needed is an integrated approach to weed management that includes a range of chemical and non-chemical weed control options.

The common message that is recommended by researchers in the area is to adopt a phase farming approach, i.e. a non-crop phase (e.g. two to three years) followed by a crop phase (two to five years) and to use a mixture of herbicide and non-herbicide weed control or an Integrated Weed Management approach. However, this simple message does not suit all growers. It is not possible to give prescriptive solutions to growers, as there are a wide range of attitudes to each solution. Rather it is necessary to work closely with to work through a range of solutions that are specific to each farm. This 'systems approach' has been adopted by staff of the Department of Agriculture to address the problem of herbicide resistance.

1. Chemical methods:

- Double knock strategy: i.e. use glyphosate followed by Sprayseed, so that weeds which survive glyphosate, are killed with Sprayseed.
- Rotate herbicides: Don't use the same herbicide repeatedly if it works, as resistance will develop later.
- Crop topping - topping pulses after the pulse seed has matured is a good way to prevent some weeds from setting seed (Mingenew-Irwin Group Inc., unpublished).

2. Non-chemical methods:

- Competitive manipulation so that crops have a competitive advantage, by using high seeding rates and narrow row spacing, delay sowing after weed germination has occurred, choose crop species that are naturally better competitors or ensuring competitive crop agronomic practices.
- Reducing weed seed viability, by burning header rows with a hot burn (this practice must be used judiciously however, to avoid soil erosion issues).
- Include pasture phases or other non-cropping phases in your rotation such as green manuring, cutting for hay, etc. In these non-cropping phases do not allow weed seed set. Delay sowing until there has been a germination of weeds - if possible.

3. Mechanical methods:

- Seed collection at harvest. Seeds can then be cleaned from grain prior to delivery. Sheep grazing also remove fresh viable seeds and prevent entering the seed bank.
- Cultivation to kill weeds (allows early germination of weeds and delay of sowing). Encourage germination by tickle or light cultivation, which changes seed position in soil and bury them to stimulate better germination of weeds, then use the double knock strategy.
- Prevent weed seed introduction, by ensuring seed is clean before sowing, not taking crop seed from an area of known resistance problems and feeding stock in a designated feed area (Stewart 2001).

Effectiveness

1. Chemical methods:

Knockdowns have 95 per cent (70-98 per cent) effectiveness and selective herbicides have 85 per cent (65-95 per cent) control for managing young ryegrass plants. Crop topping has an 80 per cent (70-95 per cent) control for managing ryegrass seed set (Stewart 2001).

1. Non-chemical methods:

– Competitive manipulation: Agronomic manipulation has been difficult to define as it has been incorporated with other forms of weed management (e.g. herbicides), however, high crop seeding rates have been shown to reduce weed seed production in the order of 30 per cent (Stewart 2001).

Weed management tools for depleting the annual ryegrass seedbank and preventing the addition of fresh, viable seed to the seed bank (Stewart 2001)

Weed management tool	% control
Stubble grazing	Low, less than 20%
Autumn burn - low fuel/or heavy grazing	Low (10-30%)
Autumn burn - high fuel, no grazing	50% (20-95%)
Autumn burn - modified header trail	60% (30-85%)
Autumn burn - seed cart dumps	40% (20-80%)
Autumn tickle with delayed sowing and knockdown	40% (20-80%)

– Include pasture phases or other non-cropping phases: Effectiveness depends on management tools used during these phases. Pasture phases usually include grazing by sheep, by which weed control then depends on the length of the pasture phase (Pannell *et al.* 1999). Grazing has a low percentage control for managing young ryegrass plants and reduces seed set (Stewart 2001).

Weed management options for ryegrass seed set control (Stewart 2001)

Weed management tool	% control
Pasture Spray topping	85% (65-95%)
Green manure crops	95% (70-98%)
Brown manuring	95% (70-98%)
Hay cutting	80% (65-95%)
Hay cutting with glyphosate	85% (75-95%)
Crop topping	80% (60-90%)
Hay freezing	90% (70-95%)

2. Mechanical methods:

– Seed collection at harvest: It is estimated that 75 per cent or more of ryegrass present at harvest passes through the harvester. Effectiveness of weed control depends on whether seed is caught, burnt in header trails or a total burn is conducted (Pannel *et al.* 1999).

– Sheep grazing: Low percentage control for managing young ryegrass, with less than 20 per cent control for reducing seed set, depleting annual ryegrass seedbank and preventing addition of fresh viable seeds.

– Cultivation to kill weeds: Cultivation - full cut impact on germinated weeds 80 per cent (70-95 per cent) control for managing young ryegrass plants (Stewart 2001).

Department of Agriculture extension messages have increased the awareness of the risk of glyphosate (e.g. Roundup®) resistance. Adoption of the double knockdown strategy has improved as a result. The majority of growers are now aware of the threat that wild radish poses to the farming system. The Department is currently working closely with growers to develop workable solutions such as seed destruction at harvest, crop rotation, alternative herbicides (e.g. Diuron) and crop competition. Recent extension has seen growers look to ryegrass as an opportunity to maximise livestock production while in the pasture phase.

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ISSUE 8: NON-WETTING (WATER REPELLENCE)

Cause

Hydrophobic materials (including fungal hyphae, waxes and other organic matter) consist of long hydrocarbon chains, which are chemically water repellent. Waxes diffuse out from particulate organic matter under wetting-drying and heating-cooling cycles, during false breaks in the seasonal climate. These hydrophobic materials coat soil particles and soil aggregates giving the soil a water repellent property (Moore and Blackwell 1998). Microbes are responsible for selective degradation of non-polar waxes from plant materials, into polar waxes, which contribute to water-repellent conditions (Farmnote 109/96). Micro-organism cultures were extracted by Franco *et al.* (1994), who isolated actinomycete (fungi) to be responsible for degradation of non-polar waxes. Lupin plant residue is also a known source of hydrophobic compounds.

Coarser sands with larger particles have a lower surface area to volume ratio than clays and sandy loams, making sandy soils highly susceptible to being covered by alkanes and fatty acids. Clay generally has a surface area too large to be covered by organic matter; its presence therefore decreases the water repellence properties of soils (Moore, Blackwell and Carter 1997).

Extent

Non-wetting mainly affects deep sands, sandy surfaced soils and sandy duplex soils. The actual extent of the problem has not been measured, as this would be a very expensive and time-consuming process. The following estimates are based on the on the qualified soil groups allocated to the Department of Agriculture's soil-landscape mapping:

Table 8.1: Non-wetting susceptibility (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Soils highly susceptible to non-wetting	
Subregion		**ha**	**%**
Greenough	1,776,237	245,985	13.85
West Midlands	742,584	312,228	42.05
Moore River	1,279,578	207,032	16.18
Yarra Yarra	921,222	10,080	1.09
TOTAL	**4,719,621**	**775,324**	**16.43**

Over 40 per cent of soils susceptible to non-wetting in the NAR are found in the West Midlands zone, being the area where sandy duplex and deep sand profiles dominate.

Impacts

The impacts of non-wetting soils are summarised by Moore and Blackwell (1998) on page 56 of 'Soilguide'.

Non-wetting reduces infiltration rates (especially early in the growing season) and this can result in increased run-off. Impacts of reduced infiltration are:

- lower soil moisture;
- crop and pasture germination and establishment problems, including delayed and uneven establishment;

- poor crop and pasture growth;
- patchy crop performance;
- poor ground cover increasing erosion risk; and
- an increase in weed establishment.

Impacts of increased run-off are:

- increased water erosion risk;
- increased risk of nutrient export;
- potential for pesticide and herbicide run-off; and
- concentration of run-off water can lead to rapid point-infiltration (flow fingering) below the root zone that can then recharge watertables.

Management options

Depending on the circumstances

1. **Furrow sowing (adapt):** Installing furrows when cropping to harvest water and ensure even wetting around the seed - see pages 60-62 of 'Soilguide' (Moore and Blackwell 1998) or Blackwell (1997).
2. **Claying (recover):** Addition of clay to the topsoil to increase surface area and reduce repellence – see page 63 of 'Soilguide' (Moore and Blackwell 1998; Carter and Hetherington 2002).
3. **Perennial vegetation (contain):** Establishing perennials reduces problems, as there is no annual germination.
4. **Soil wetting agents (recover and contain):** Addition of agents that lower surface tension (usually only done in bands along seeding rows, due to the cost of wetting agents).

In addition:

- Lime and gypsum are often mentioned as possible solutions, but have been very disappointing in most trials in Western Australia (Blackwell 1996).
- Repellent soil layers can be diluted with deeper, non-repellent soil to reduce the problem, but this can lead to a large wind erosion risk and is not a long-term solution (Blackwell 1996).

Effectiveness

1. **Furrow sowing:** Easiest solution for better cropping (Blackwell 1996). Can be quite effective but there are increased risks of erosion, herbicide concentration, leaching and waterlogging.
2. **Claying:** Best long-term solution (Blackwell 1996). Highly effective on light textured topsoils containing < 10 per cent clay, not very effective on heavier textured topsoils. However, a suitable source of clay (non-saline dispersible kaolinite) is required in close proximity to the soil (high transport costs). Claying in the NAR has produced mixed

results however, and further research needs to be conducted to determine causes of the variability in effectiveness (D. Carter, pers. comm.).

3. **Perennials:** Avoids the problem, as there is no need for annual germination.
4. **Wetting agents:** Can be effective but are currently too expensive for broad-scale agriculture.

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ISSUE 9: NUTRIENT LOSS AND EUTROPHICATION

Cause

Eutrophication is the nutrient enrichment of waterways that stimulates primary production of algae and macrophytes, which leads to deterioration of water quality. Nutrients, particularly phosphorus (P) and nitrogen (N), enter waterways through leaching of surrounding catchment soils (Weaver and Summers 1998). Phosphorus is essential for energy storage and transfer systems in plant cells, thus early plant growth is particularly dependent on P as it is needed for rapid cell division and expansion (Bolland *et al.* 2003). P entering aquatic systems effectively stimulates rapid primary production by allowing rapid cell division and expansion.

Factors affecting nutrient loss include type and form of nutrient applied, rainfall, uptake by plants and water movement. The major factor is rainfall, which cannot be controlled, increasing water flow, erosion and nutrient discharge into waterways. Soil type affects the rate of water movement through it and retention of nutrients, with soils prone to leaching being the most susceptible to nutrient loss. Phosphorus Retention Index (PRI) determines the capacity of the soil to adsorb P, thus high PRI reduces the amount of P lost through leaching, but also decreases its availability to plants (Weaver and Summers 1998).

Extent

Phosphorus and nitrogen are the main nutrients contributing to eutrophication of surface and groundwater. These nutrients may leach through sandy soils and enter groundwater and surface water via groundwater discharge. Phosphorus, attached to clay particles, may also enter surface waters directly via soil erosion. Current estimates are that up to 10 per cent of phosphorous added as fertiliser is lost in drainage and approximately 70 per cent of this comes from previous applications stored in the soil (Harris 1996).

Factors contributing to eutrophication have been outlined by Tille *et al.* (2001) as follows:

- the presence of permanent waterways, wetlands and estuaries;
- intensive agricultural and urban development;
- large areas of sandy soils with poor nutrient retention ability;
- widespread waterlogging; and
- artificial drainage systems that rapidly move water and nutrients into susceptible waterways.

Nutrient export pathways, and the subsequent risk of eutrophication, may also be related to areas of heavier textured soils which are left in a state that is prone to soil erosion. There may also be other bypass pathways where nutrients arrive in streams from macropores, and largely avoid the soil mass and buffering it provides against nutrient loss.

The extent of nutrient loss throughout agricultural areas is very difficult to measure directly and may be best determined by a spatial analysis of soil nutrient levels and nutrient retention capabilities, land use and topographical and hydrological attributes. These may be subsequently calibrated through an assessment of nutrient levels in the major regional waterways. Soil test results at the required resolution are difficult to obtain, are not generally current and are generally provided only in terms of broad regional data. Nutrient loads of some waterways are monitored, and this may provide some indication of actual nutrient export rates.

In the absence of comprehensive soil, land use, topographical and hydrological data, estimates of the susceptibility of soils and landscapes to export phosphorus based on the land units allocated to the Department of Agriculture's soil-landscape mapping provide some indication of inherent nutrient loss potential.

It should be noted that the table below needs to be corrected for catchment size. The smaller the catchment measured, the higher the load of nutrient is per unit area and the higher the concentration of nutrient will be. Whilst scale is important, so are episodic events, particularly for inland catchments which under average conditions appear insignificant. Large inland events may, however, deliver significant quantities of nutrients to drainage systems. Averages or measures of central tendency are useful and needed statistics for regional analysis, but may mask some important characteristics related to nutrient delivery pathways and potential management options

Table 9.1: Phosphorus loss hazard in the NAR (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Soils highly susceptible to non-wetting	
Subregion		ha	%
Greenough	1,776,237	121,050	6.81
West Midlands	742,584	75,855	10.22
Moore River	1,279,578	214,266	16.75
Yarra Yarra	921,222	10,080	14.43
TOTAL	**4,719,621**	**544,109**	**11.53**

*Evidence is mounting that heavier soils may have been underrated in the past and heavy fertilisation and intensification of animal industries has resulted in an increase in risk.

Estuaries or water bodies at risk in the NAR include Moore, Hill, Irwin, Greenough, Chapman, Hutt, Bowes and Murchison, as well as numerous lakes. Sandy soils are predominant in these catchments. The sandy nature of the soil results in less run-off and hence lower loads of phosphorus being exported compared to heavier soils. The heavier soils that are fertilised more have lower concentrations but substantially greater run-off with the net result of similar phosphorus loads between sandy and clay soils.

There is a trend for the average export of nutrient from a catchment to decrease with increasing catchment area. This is related to in-stream assimilation effects (travel time, sedimentation, biological uptake, nutrient spiralling) and the increasing influence of uncleared and unfarmed land as catchment size increases. In agricultural areas, the rate of stream flow is estimated to have increased by as much as a factor of 3 to 4 since clearing (ARMA 1999). This increased flow can be further heightened by climatic conditions, such as wet or dry years and episodic rainfall events, which can lead to wide variations in river flow levels and associated movement of pollutants.

Impacts

The impacts of eutrophication are summarised by Tille *et al.* (2001) and Weaver and Summers (1998).

Most of the impacts of nutrient loss and eutrophication occur off-site, and include:

- algal blooms and the formation of algal mats on the water surface;

- oxygen depletion of water, which may lead to the death of fish and crustaceans;
- damage to seagrass meadows in the marine environment due to shading by algal blooms;
- toxins from blue-green algae (*Nodularia, Microcystis, Ocsillatoria*) pollute waterways and may kill fish, birds and livestock and are a human health hazard;
- waterways may be closed to fishing and recreational uses, affecting income from fishing, tourism and real estate values;
- unpleasant odours;
- nitrate toxicity of groundwater supplies where nitrogen reaches critical levels; and
- loss of groundwater supplies for human use, or more expensive treatment to ensure continued use.

On-site impacts include:

- loss of soil fertility, due to water erosion and/or through the inefficient use of fertilisers;
- toxic effects on crops when groundwater with high nutrient levels is used for irrigation;
- toxins from algae contaminate farm water supplies, endangering livestock;
- nitrates in groundwater can endanger livestock; and
- inappropriate and inefficient fertiliser use leading to decreased farm profitability.

Nutrient export in the NAR is largely influenced by non-point source discharges from broad scale agricultural operations or urban developments, but point sources may also be significant locally. These include intensive agricultural developments, effluent from septic tanks, piggeries, stock holding yards and feedlots.

Management options

1. **Monitoring:** Ongoing monitoring of river water quality, particularly in association with known point sources of pollution.
2. **Fertiliser management (Recover and Contain):** Match fertiliser applications to plant requirements by using soil testing, tissue testing or rapid sap tests as appropriate (see Farmnotes by Summers in the references). Manage the timing and method of application of fertiliser to avoid run-off and leaching.
3. **Using alternative fertilisers (Recover and Contain):** Including coarse rock gypsum to supply sulphur rather than superphosphate; non-soluble rock phosphate on acid sands on poorly drained areas.
4. **Soil amendments (Contain):** Use of soil amendments to improve nutrient retention (Tille *et al.* 2001)
5. **Streamlining and filter strips (Recover and Contain):** Fence off and establish buffer strips to filter nutrients and protect waterways. The width of buffer strip recommended varies with land use and soil type and should also consider topographical attributes such as convergent or divergent landscapes, and hydrological attributes such as stream order. Refer to Heady and Guise (1994) and Tille *et al.* (2001).

6. **Perennials (Contain):** Perennial pastures minimise losses from leaching as they are able to access nutrients over a longer period and access nutrients at greater depth than annual species.
7. **Drainage (Contain):** By reducing waterlogging, plant uptake of nutrients is increased but may increase nutrient export, depending on design and a range of climatic and soil characteristics (Tille *et al.* 2001).
8. **Constructed wetlands (Contain):** Wetlands can be constructed to slow water flows, trap sediment and assimilate nutrients. Criteria for their design using examples relevant to the Ellen Brook Catchment are presented in Deeley (2000).
9. **On-farm re-use systems (Contain and Adapt):** Management of surface water to harvest and store water and nutrients for use on-farm. Can be integrated with engineered options for drainage and water erosion control.
10. **Control of water erosion (Contain):** Management options are outlined in the Water Erosion section of this document.
11. **Treating point sources (Contain):** Storage and disposal of effluent from piggeries and intensive agriculture, e.g. feedlots. Guidelines set out in Dairy Industry Strategy working Group (1998) and Latto *et al.* (2000).
12. **Controlling algal blooms in on-farm water supplies (Contain and Adapt):** Silt and manure traps at the farm inlet, use of block alum and barley straw to inhibit algae; chemicals such as Simazine and calcium hypochlorite, to kill algae or for low algae levels, skimming algae and scum off the water. Farmnotes on this issue include:
    - 84/85 Emergency chlorination of farm dams
    - 11/87 Skimming polluted dams – a successful two stage system
    - 103/89 Grass filter strips to prevent dam pollution
    - 43/94 Toxic algal blooms

Effectiveness

1. **Fertiliser management:** Highly effective, particularly for phosphorus with many soils already having moderate to high phosphorus status and not requiring additional applications.
2. **Using alternative fertilisers:** Generally effective, when combined with management option 1. Rock phosphate does not release enough phosphorus on most soils but is a good option for a small area of acid sands on poorly drained areas on the Coastal Plain. For example, 1 and 2 have decreased phosphorus application in the Peel-Harvey by 33 per cent between 1982 and 1986 and reduced phosphorus export from the catchment by 30-40 per cent (Tille *et al.* 2001).
3. **Soil amendments:** Highly effective at reducing phosphorus loads with the added benefit of increasing pasture production.
4. **Streamlining and filter strips:** Effective but alternative watering points may be required for livestock.
5. **Perennials:** Effective for grazing systems and between perennial horticultural crops. Perennial buffer strips of only 3 metres wide, which have controlled grazing can reduce nutrient and particulate movement by as much as 90 per cent. Substantial increases in

animal production have been reported because the pasture production is greatly improved at the times of year when there is a feed gap.

6. **Drainage:** Effectiveness is dependent on soil properties and hydrological processes that are operating and may actually increase nutrient export in some cases. Subsurface drainage can reduce nutrient and particulate run-off under suitable environmental conditions, where soils continue to provide nutrient adsorption sites and where leaching is the dominant hydrological pathway.
7. **Constructed wetlands:** Most effective if used to filter run-off from small agricultural catchments rather than from large areas or point sources or where the ratio of wetlands to catchment area is high.
8. **On-farm re-use systems:** Management of surface water to harvest and store water and nutrients for use on-farm. Can be integrated with engineered options for drainage and water erosion control.
9. **Control of water erosion:** Refer to the Water Erosion Section.
10. **Treating point sources:** Highly effective.
11. **Controlling algal blooms in on-farm water supplies:** Effective but some methods restrict use of water and others require action before blooms occur to be effective.

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ISSUE 10: REMNANT VEGETATION DECLINE

Cause

Loss of remnant vegetation has occurred rapidly since the arrival of Europeans in Australia. Most of the land was converted to agricultural pastures and crops. Areas of native vegetation were reduced to localised fragments, roadsides, swamps, rocky slopes and hilltops. This land was not cleared because it was unsuitable for cropping and grazing. Remnant vegetation is surrounded by either agricultural land or urban development, which has additional impacts on its natural structure, composition and density leading to further decline. These activities have caused interruptions in fire regimes, overgrazing, weed infestation and further losses through woodcutting (Bastock 1999).

Clearing since European arrival has reflected settlement patterns, where most areas capable of supporting development are predominantly in higher rainfall regions with most fertile soils. In NAR, shrubby understoreys have been removed by frequent fires, invasion of exotics species and overgrazing. Agricultural and pastoral development has resulted in major changes in extent and condition of landscapes. Clearing was encouraged by the government and was often a condition of land tenure (Australian Native Vegetation Assessment 2001).

Extent

Approximately 4,700,000 hectares (86 per cent) of land has been cleared across the NAR, with 672,260 ha (14.2 per cent) remaining as remnant vegetation on private land. Many remnants found on private land in the NAR are highly fragmented. The largest tracts of remnant vegetation occur in the West Midlands and are a combination of reserves and vacant crown land.

Remnant vegetation associations are diverse across the NAR, with the greatest biological diversity found in the Mt Lesueur area. Woodland in particular has been significantly affected by the expansion of agriculture. Many areas of woodland associations, such as York gum and salmon gum, have been lost over the past 150 years due to their association with preferred soil types for agriculture. In the Moore River Catchment for example, 93 per cent of the medium woodland York gum and salmon gum association has been cleared (Alderman and Clarke 2003). Valley floor vegetation associations were initially targeted for clearing not only due to soil type but also landscape position. Loss of native vegetation, due to the activities of industries other than agriculture, is minimal in the NAR.

Table 10.1: Total area of remnant vegetation on private land in the NAR (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Total pre-European (ha)	Native vegetation currently on private land	
Subregion			ha	%
Greenough	1,776,237	1,775,496	195,830	11.02
West Midlands	742,584	742,363	175,542	23.64
Moore River	1,279,578	1,279,196	196,311	15.34
Yarra Yarra	921,222	921,222	104,576	11.35
TOTAL	**4,719,621**	**4,718,277**	**672,260**	**14.24**

Impacts

Many native vegetation types have been extensively cleared and consequently many species of plants and animals have disappeared, or have become rare or endangered (Holt and Bradby 2000). The current level of habitat loss and degree of fragmentation leaves insufficient natural vegetation resources across various landscapes to support viable populations of many species (Beecham 2002). The NAR has vegetation associations that are fragmented, the majority of which are below 10 ha.

Altered hydrology is a serious and difficult problem that has arisen from land clearing. Increasing levels of stress to native vegetation due to secondary salinity, waterlogging and inundation is becoming widespread, particularly in lower landscape areas, leading to the complete loss of vegetation in these areas. In addition to this, the prospect of using waterways as receival points for groundwater drainage and pumping schemes has the potential of delivering excess salty water and increased water acidity levels, thereby significantly affecting aquatic environments and riparian zones, needs to be considered (Beecham 2002).

Ongoing vegetation decline can be attributed to the effects of land salinisation, legal and illegal clearing, poor management including a lack of fencing and stock access, spray drift and fertiliser movement from agricultural land, unsuitable burning regimes, weed invasion, woodcutting, destructive recreational activities and feral animals.

Management options

1. **Salinity and waterlogging management (Contain):** Management strategies to protect remnants from salinity and waterlogging in most cases can only be tackled in the context of the overall catchment. Acquiring a detailed knowledge of catchment hydrology and geology is essential. Salinity management strategies to consider include strategic revegetation in high recharge and water gaining sites, surface water and groundwater engineering options, as well as low recharge farming systems such as perennial pastures and farm forestry. These need to be part of an integrated landscape approach where they are likely to have the greatest impact (Beecham 2002). (See Dryland Salinity Section for management options.)

2. **Corridors (Recover and Contain):** Lack of connectivity between remnants has created a multitude of isolated remnants, with a limited ability to sustain viable populations of flora and fauna. Wildlife corridors protect and connect existing remnant vegetation patches using paddock boundaries, drainage lines and shelter belts as corridors (Lefroy *et al.* 1991).

3. **Fencing remnants (Recover and Contain):** Excluding stock from remnants allows the understorey to regenerate and reduces the introduction of weeds, which out-compete native species. Alternative shelter belts for stock protection can be established by planting fast growing species in areas where stock regularly camp.

4. **Weed control (Recover):** The maintenance of intact native vegetation canopies and low nutrient systems encourages weed resistance in remnant vegetation. The use of herbicides in remnants must be treated with caution.

5. **Strategic revegetation (Recover):** Targeting revegetation to address specific farm and catchment issues, such as groundwater discharge and recharge.

6. **Commercial species buffers (Recover and Contain):** Buffering remnants ensures minimal weed encroachment from agricultural land and provides a way of limiting the effects of agricultural fertiliser and spray drift on remnants (edge effects).

Effectiveness

1. **Salinity and waterlogging management:** Effective only if the scale of intervention is adequate and there are sufficient farming system based activities to reduce the overall effect of salinity and waterlogging in the local catchment.

2. **Corridors:** Corridor effectiveness depends largely on the width of the corridor itself. A corridor should be planted as wide as is practicable to reduce edge effects (Lambeck 1999). Using drainage lines as the base for corridors will help to limit the effects of flooding, trap sediment, provide habitat and stabilise river banks and this will allow the safe disposal of surface water, where necessary.

3. **Fencing remnants:** Is effective if stock exclusion is maintained. Poor recruitment of woodland and understorey species even when remnant areas are only lightly grazed suggests this is required for success (Lambeck 1999).

4. **Weed control:** Can be effective if closely monitored and controlled with appropriate methods. Often continuous management is required to keep weeds at a minimum.

5. **Strategic revegetation:** Most effective for salinity management when used in small problem areas such as sandplain seeps. For biodiversity values, direct seeding gives the most natural effect to a functioning ecosystem, which are rarely possible to reproduce (Hobbs *et al.* 1993). Retaining, enhancing and protecting vegetation in high recharge zones will only be effective with broad scale intervention that includes perennial species incorporation in farming systems. In small subcatchments the impacts of retaining strategic vegetation for this purpose may be more greatly felt.

6. **Commercial species buffers:** Effective only if a significant buffer (two rows of trees is insufficient) is established and maintained and management guidelines are followed.

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ISSUE 11: SOIL ACIDITY

Cause

Soil acidification is a natural process that occurs during weathering. Some soils are naturally acid, such as acid sulfate soils, as mentioned earlier. Acids produced from the carbon and nitrogen cycle, dissolve the parent rock producing acid soils. Nitrate leaching is a major cause of soil acidification. Natural ecosystems tightly control the nitrogen cycle so that nitrate is not produced in excess and leached from the system. Agricultural systems have added nitrate or nitrate producing legumes such as lupins and clover and have changed the nitrogen and carbon cycle processes.

As nitrate is very soluble, it leaches through the soil quicker than plants can uptake it, therefore leaving behind acid soils. The process of nitrification, converting organic nitrogen or ammonium into nitrate, produces acidity, thus the addition of ammonium fertilisers and organic acids contribute to increased acidity (National Land and Water Resources Audit 2001). Good farming practices may also increase soil acidity, due to the yearly removal of alkali plant materials (Hunt and Gilkes 1992).

Soils have an important ability to resist pH change, called buffering capacity. Buffering capacity determines which soils are most at risk from acidification. The greater the clay content in the soil the greater the soil's ability to withstand an increase in acidity or the greater its buffering capacity. For this reason the sandy soils of the region are most at risk, including sandy red loams and gravelly sands (Moore *et al.* 1998).

Extent

Soil acidity is a widespread problem in Western Australia, including the NAR. Activity associated with identifying and ameliorating acidity at the surface has rapidly increased in Western Australia, due in a large part to Department of Agriculture extension programs. According to the National Land and Water Resources Audit (2001), 11 per cent or 2.12 million hectares of south-west topsoils were strongly acid (pH < 4.8) and another 78 per cent or 15 million hectares had pH between 4.8 and 5.5.

Soil acidity is most prevalent in sandy soils with a low capacity to buffer pH change. Although the recognition and treatment of surface acidity is becoming common practice, the identification and remediation of subsoil acidity (10-30 cm) is not. Cost effective techniques for remediation of subsoil acidity are still being developed and trialled (Gazey, pers. comm. Project DAW00014). The following zone surface and subsurface pH estimates are based on the qualified soil groups allocated to the Department of Agriculture's soil-landscape mapping.

Table 11.1: Acid soils in the NAR (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Topsoils currently strongly acid (pH_{Ca} < 4.5 at 0-10 cm)		Subsoils currently strongly acid (pH_{Ca} < 4.5 at 50-80 cm)		Soils with a high risk of subsurface acidification	
Subregion		**Ha**	**%**	**Ha**	**%**	**Ha**	**%**
Greenough	1,776,237	25,540	1.4	0	0	777,063	43.75
West Midlands	742,584	42,263	2.1	31,177	4.2	447,690	60.29
Moore River	1,279,578	15,560	3.3	0	0	391,964	30.63
Yarra Yarra	921,222	76,946	8.4	39,945	4.3	279,159	30.30
TOTAL	**4,719,621**	**160,309**	**3.40**	**71,122**	**1.51**	**1,895,876**	**40.17**

Over a third of the soils with a high risk of subsurface acidification are found in the Greenough subregion where pale deep sand and yellow deep sand profiles are dominant. Significant areas also occur in the Moore River and West Midlands.

Impacts

Soil acidity impacts on agricultural production by (Moore *et al.* 1998; Dolling *et al.* 2001):

- Increasing the availability of the toxic elements, especially aluminium (manganese toxicity due to low pH has not been observed in WA) which stunts root growth.
- Decreasing the availability of nutrients such as phosphorus, potassium, calcium, magnesium, molybdenum and copper.
- Reducing microbial processes, for example, microbes involved in the decomposition of organic matter that supplies nitrogen, phosphorus and sulphur.
- Increasing fungal diseases of plants, although some types of fungal diseases can decrease, for example, 'take all'.

There is a lack of information regarding off-site impacts of soil acidity and further study is required. However, soil acidity has some impact on at least the following, from Dolling *et al.* (2001):

- increased dryland salinity, waterlogging and flooding;
- increased nitrate pollution of groundwater and reduced water quality;
- reduced plant yields, farm income, land values and domestic/export earnings;
- reduced plant species options for agriculture;
- reduced vegetation cover and accelerated run-off and erosion;
- irreversible degradation of the clay minerals of soil, hence reduced fertility;
- declining pH of waterways and aquatic environments; and
- increased infrastructure cost as a result of increased salinity, waterlogging, flooding and sediment on road and in drains.

While acid soils are a natural phenomenon in some areas in the NAR, acidity is accelerated by some farming practices, including adding acid fertilisers (particularly Agras and DAP), alkali product removal and leaching of nitrate (Dolling *et al.* 2001).

Management options

The management options for soil acidity are summarised on pages 128-140 of 'Soilguide' (Moore *et al.* 1998).

1. **Adding alkaline reagents (Recover and Contain):** Adding lime as top dressings (to increase surface soil pH) and by banding or incorporating at depth (to increase subsoil pH) is the major management recommendation. Other alkaline reagents (e.g. fly ash from cement kilns, dolomite) are alternative options.

2. **Reduce rate of acidification (Contain):** Several management methods will reduce the rate of acidification. Firstly, reducing the rate of product removal from the paddock will reduce acidification by reducing the export of cations (that are replaced by hydrogen ions [acid] in the soil). An example is to limit the highly acidifying operation of hay cutting to alkaline soils and to distribute hay as feed on to acid paddocks. Secondly, reducing or removing the input of acidifying fertilisers (ammonium-based nitrogen and elemental sulphur) will decrease acidification rates. Thirdly, reducing or stopping nitrate leaching will decrease acidification rates. This can be achieved by reducing or splitting nitrogen applications to the amount crops can realistically use and by planting perennials that draw on nitrate, water and alkaline nutrient reserves from deeper in the soil profile than annual plants are able to.

3. **Plant acid tolerant species (Adapt):** Choosing species and varieties that can tolerate lower pHs can maintain profitability over the short term. This strategy can be used in conjunction with amelioration.

Effectiveness

1. **Adding alkaline reagents:** Proven effective and economically viable for surface acidity, and also effective at ameliorating the subsurface with time (Tang and Rengel 2001). Surface liming is quite effective at maintaining appropriate pH in the subsurface if a program is started before significant subsurface acidity has developed. The effectiveness of using alkaline reagents to ameliorate subsoil acidity is currently being investigated. Other alkaline reagents are effective, e.g. fly ash from cement kilns, dolomite but are often not as economically viable or available in large quantities.

2. **Reduce rate of acidification:** Part of an integrated solution in conjunction with adding alkaline reagents. It is a valuable management option as part of the farming system but will not solve soil acidity. It may not be economical in some circumstances for farmers to attempt actions, as it may be more expensive to use other non-lime alkaline reagents, compared to the current practice of using both acidifying nitrogen fertilisers and lime.

3. **Plant acid tolerant species:** Short-term measure only, it is ineffective at reversing acidification as it allows soil acidification to continue to occur.

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ISSUE 12: SOIL FERTILITY DECLINE

Cause

Most soils of Western Australia have low fertility as they are ancient and highly weathered. Nitrogen is easily leached from the soil profile; phosphorus on the other hand is highly residual but mostly unavailable to plants. The continual removal of potassium and sulphur in agricultural produce and the use of non-potassium and low-sulphur fertiliser, has resulted in soil nutrient decline (Bolland 1998).

Acute nutrient loss is also related to wind and water erosion. Leaching or surface water run-off can cause substantial losses. Water erosion selectively depletes silts and clays from soils, and silts and clays commonly have nutrients adsorbed to them (Coles and Moore 1998). Wind erosion has also been a significant cause of removal of material from paddocks that contain macro and micro-nutrients, which are literally blown away. Loss of nutrient 'availability' can also occur for some nutrients by fixation into organic matter and reactions with soil minerals (Moore *et al.* 1998).

Western Australian soils consist of varying amounts of hydrous iron and aluminium oxide minerals, due to weathering, which have a high affinity for sorbing soluble P (Allen 2002). Phosphate is adsorbed onto soil surfaces when the oxygen atom from the phosphate ion donates a lone pair of electrons to metal atoms such as iron and aluminium. The phosphate ion replaces surface ions such as hydroxide, sulfate, bicarbonate and molybdate, which are attached to these metals, due to its stronger adsorbing force. P slowly diffuses towards the interior of the particle so that it becomes less available to plants. Effectively, phosphorus is immobile in Western Australian soils, which has resulted in native plants developing ways of retrieving phosphate from soil.

Most soils have a low capacity to retain anions, therefore, loss of nitrogen through leaching occurs mainly as nitrate (NO_3^-). Movement of water downward through the soil profile causes the leaching of nitrates. The magnitude of N loss is proportional to the concentration of nitrates in soil solution and the volume of leaching water.

Minimising nitrate leaching in soil requires knowledge of the nitrogen cycles, controlling the timing of nitrate formation, understanding soil and climatic conditions which impact nitrate formation, and nitrogen uptake patterns of the crop being grown (Gaidos 1996).

Extent

The native soils of Western Australia are some of the most inherently infertile in the world, and consequently the fertility of many agricultural soils here has substantially increased by adding chemical fertilisers and organic matter from crop and pasture residues to the infertile native soils. However, a lack of maintenance of soil fertility levels at recommended concentrations has been identified as a threat to agricultural production.

The rate of soil fertility decline is variable, relative to the type and intensity of land use and associated nutrient losses. This is because the nutrient requirements and product removal vary significantly between agricultural land uses. The successful continuation of agricultural activities requires that the nutrient balance in soils be maintained or improved, and that nutrients removed via agricultural products be replaced both naturally and through fertiliser addition as required. While no comprehensive data on the extent of soil fertility decline is available, generalised assessments of farm gate nutrient balances and organic carbon ranges have been made for the south-west of Western Australia in the Australian Natural Resources Atlas (2001).

Table 12.1: Generalised assessments of farm gate nutrient balance for two broad land uses within Western Australia's agricultural zone [where negative (inputs < exports); neutral (inputs = exports); positive (inputs > exports)] *

Nutrient	Grazing	Cropping
Nitrogen	Positive	Positive – neutral
Phosphorous	Positive – neutral	Neutral – positive
Potassium	Negative – positive	Negative
Sulphur	Positive	Positive – neutral
Calcium	Positive	Positive
Magnesium	Neutral	Negative – neutral

* From Australian Natural Resources Atlas 2001.

Impacts

Allowing continued depletion of nutrients from currently fertile paddocks will eventually reduce yields and decrease the productivity and quality of future crops and pastures (Falconer and Bowden 2001). Off-site effects of nutrient loss can include soil acidification and nitrification of water supplies caused by nutrient leaching. Declining fertility is linked to declines in soil structure, increased levels of erosion and secondary salinity. In addition, run-off containing nitrogen and phosphates have been linked to stream and groundwater pollution.

Management options

Nutrient management has moved soil fertility beyond the 'build up' phase into a 'maintenance' phase over much of Australia's intensive agricultural region. Site-specific nutrient management now replaces broad district fertiliser guidelines (Australian Natural Resources Atlas 2001). Short-term thinking for meeting immediate demands goes wrong when early treatment could prevent a long-term, expensive to cure, problem from arising (Bowden 2003).

1. **Monitoring:** Know the nutrient, organic carbon status and pH status of the soil.
2. Base **fertiliser decisions (Adapt)** on the standard methods (e.g. soil and/or tissue testing, symptoms, etc.) appropriate to the nutrient or nutrients in question. These nutrient management decisions are especially important for requirements of higher input, intensive systems of land use.
3. **Additions (Adapt):** To the soil include fertilisers (supplying adequate amounts of essential plant nutrients), soil ameliorants (e.g. lime, dolomite and gypsum, manure and biosolids that chemically and physically improve the soil) and the use of legumes to increase soil nitrogen status.
4. **Organic matter content (Recover):** Follow pasture and cropping management recommendations to maintain and build on levels of organic matter on the site.
5. **Soil erosion (Contain):** Reduce or prevent soil erosion to lower acute losses of nutrients.
6. **Water management (Contain):** Decrease leaching and run-off by improved soil and water management.

Effectiveness

1. **Monitoring:** Regular monitoring assists the land manager to identify nutrient deficiencies and toxicities, pH status and organic carbon status. This information can help determine the appropriate management option. Monitoring alone does not solve nutrient decline issues.
2. **Fertiliser decisions:** To anticipate fertility problems so that appropriate and timely steps can be made to address them. Losses become critical when the paddock soils are already marginal or deficient in nutrients.
3. **Soil additions:** Adding chemical and/or organic fertilisers provides the best solution for maintaining soil nutrient status. Leguminous crop and pasture species provide important additions of nitrogen, in organic matter, to soils.
4. **Organic matter content:** By maximising the levels of pasture and crop residues (within the stubble management capabilities), soil organic matter can be maintained or improved.
5. **Soil erosion:** Improved pastures and stubble residues provide effective ground cover protection for soil, reducing erosion risk.
6. **Water management:** Crops and pastures fertilised correctly will use more water than those that are nutrient deficient.

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ISSUE 13: SOIL STRUCTURE DECLINE

Cause

Soil structure refers to the way soil particles and organic matter and the spaces or pores between them are structured. Good soil structure enables the uninhibited movement of air, water, roots and nutrients through the soil profile, promoting microbial growth and plant root penetration. However, when exposed to mechanical working (cultivation) and water, aggregate structures may break down. Water weakens the bonds between primary particles and organic matter that naturally bond soil aggregates. Air trapped in these aggregates, bursts out carrying primary particles, which travel and fill in pores and cracks. Raindrop impact forcefully causes dispersion of surface soil aggregates as well. Wetting and drying conditions in clays may develop hard crusts, or with the combination of cultivation, smearing of clay particles and compaction by machinery can cause the development of a 'plough-pan'. Subsoil compaction increases the density of soils and blocks off pores that allow air and water movements (Hunt and Gilkes 1992).

Sodicity reduces the strength of soil structures making them more prone to erosion. Clay minerals are made up of a crystal lattice with an overall negative charge. This negative charge is balanced by positive 'counterions', which are usually calcium or magnesium. These counterions can be readily exchanged by sodium ions which are present in the soil. A greater amount of water is adsorbed to the sodium ions, which causes swelling and shrinking of clay soils, recognised as mounds and holes (Quirk 1999).

Hard crusts around seeds interfere with seedling emergence (silly seedling syndrome) and subsurface compaction and plough-pan interferes with soil infiltration, run-off and plant root growth. Soil structure decline from water, cultivation, compaction and sodicity makes soils more easily erodible resulting in the loss of soil particles and development of tunnel and gully formation (Hunt and Gilkes 1992).

Extent

Soil structural instability affects about 3.5 million hectares of the South West agricultural region (Hunt and Gilkes 1992). Crusting and hardsetting is most common in medium and fine textured surface soils with clay contents between 10 per cent and 35 per cent. A high proportion of such soils in WA have inherent chemical properties deleterious to stable structure, with high exchangeable sodium percentages (sodic soils) and calcium to magnesium ratios that decrease with depth down the profile, as well as low amounts of organic matter. The following estimates are based on the qualified soil groups allocated to the Department of Agriculture's soil-landscape mapping and are based mostly on surface soil texture.

Table 13.1: The susceptibility of soils to structure decline in the NAR (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Soils with high susceptibility to structural decline	
Subregion		ha	%
Greenough	1,776,237	409,074	23.03
West Midlands	742,584	22,976	3.09
Moore River	1,279,578	124,497	9.73
Yarra Yarra	921,222	317,003	34.41
TOTAL	**4,719,621**	**873,549**	**18.51**

The most extensive areas of soils susceptible to structure decline are found in the Yarra Yarra subregion, which may be attributable to the high clay and sodium content of soils in this region. Significant areas also in the Greenough subregion, which may be attributable to soils with naturally poor soil structure that are exacerbated by cultivation practices or stock movement.

Impacts

Some impacts of soil structure decline may cause limited off-site degradation. Reduced infiltration increases run-off and evaporation from the soil surface. Where run-off water and eroded material enter streams, increased sedimentation, phosphorus export and eutrophication may result. Higher rates of evaporation may, over time, cause secondary salinity. Remedying soil structure decline in these areas is most likely to deliver public benefits.

The following impacts mainly affect the productive capacity of agricultural land:

- *Reduced infiltration* results in less plant available water as more evaporates from near the surface, which adversely influences yield potential.
- *Poor workability* increases the cost of operations and machinery wear and causes difficulties in preparing an even seed bed.
- *Delayed seeding* can occur when seeding is restricted to narrow 'windows of opportunity' with acceptable soil moistures.
- *Reduced seedling emergence* results from surface crusts, particularly for more sensitive crops.
- *Reduced aeration* caused by structure decline affecting crop growth by restricting the oxygen supply in the rooting zone.
- *Reduced trafficability* can affect the timing of operations, such as spraying and seeding.

See Needham *et al. (*1998) for further details.

Management practices strongly influence the occurrence of structure decline. These variables preclude the collation of comprehensive data on the actual extent of soil structure decline.

Management options

The principal strategy to maintain good structure in surface soils is to reduce the impact of management practices. Remedial management to restore soils with degraded structure to good condition may precede this strategy (Needham *et al.* 1998). The ideal remedial management depends on the factor(s) and process(es) causing poor structure. These are addressed in some detail in Hunt and Gilkes (1992), Needham *et al. (*1998) and Hamza and Penny (2002).

General options include:

1. **Monitor** and assess current condition using the methods listed in the above references.
2. **Minimise tillage (Recover and Contain), traffic,** operations and speed, and till only when the soil moisture status is at or below the lower plastic limit, and consider tramline farming. (See references for details on determining soil moisture status.)

3. **Minimise stock damage (Contain)** and trampling, by reducing stock numbers on susceptible soils when they are wet.
4. **Increase organic matter (Recover)** and retain stubble to protect against raindrop impact and to provide a long-term binding agent.
5. **Apply gypsum (Recover).**
6. **Deep ripping (Recover)** plus gypsum application is necessary if soil is compacted.

A combined package that makes use of some or all of the above components has recently been developed for soils of the eastern wheatbelt (Hamza and Anderson 2002, 2003; Hamza and Penny 2002).

Effectiveness

Minimising tillage by direct drilling has significant economic advantages to cultivation/seeding operations on susceptible soils in the northern wheatbelt (Blackwell *et al.* 1995). The benefits of no-till are variable, with no-till out-performing direct drill in some situations and under-performing in others. The gypsum/ripping/stubble retention package developed by Hamza and Anderson (2002, 2003) has economic benefits over untreated soils of $23/ha to $90/ha. Potential net financial benefits of up to $53/ha in sandplain areas of the NAR have been identified by using tramline-farming techniques (P. Blackwell, pers. comm. GRDC Project DAW718).

Increasing organic matter by green manuring, brown manuring and green mulching has economic and soil structure benefits, but income is lost for one year in the treated paddocks (Hoyle 2001). In particular, yield increases and early results suggest rainfall infiltration rates also increase. The benefits extended several seasons after treatment in the case of heavier soils.

No-till sowing increases infiltration significantly compared to multiple tillage. This reduces the potential for water erosion significantly on some soil types but may increase the potential for recharge (see Bligh 1998).

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ISSUE 14: SUBSURFACE COMPACTION

Cause

Subsurface compaction is due to compression from a vertical force such as cultivating machinery, livestock and overburden, and shearing and smearing from a horizontal force such as spinning and slipping of machinery wheels. Soil particles are rearranged and compressed together, with smaller silt and clay particles filling in macro-pores, which are usually filled with air. Physical forces by water menisci, causes soil particles to pull together. Shrinkage of sandy soils (self-compaction), have been observed on yellow sandy earths at Wongan Hills without any cultivation. Dry soils resist compaction slightly due to the interparticular forces, friction and fibres of organic matter that bonds soil particles together (Needham *et al.* 1998).

Subsoil plough pans form at the base of the tilled layer. 'Traffic hard pan' is more common on sandy soils that form approximately 10-40 cm below the surface, caused by heavy machinery compressing soil at depth. Compression causes soil aggregates to break and smaller silt and clay are carried through the profile until they are trapped creating a hard pan that can be impermeable to water, nutrients and plant roots (Hunt and Gilkes 1992).

Extent

Subsoil compaction can occur in different soil types and climatic conditions (Rengasamy 2000). However, susceptibility is reduced in strongly structured soils, well drained soils with high organic matter content and in drier regions where soils rarely reach the water content at which severe compaction is possible (Needham *et al.* 1998).

No comprehensive data on the extent of subsurface compaction is available in Western Australia. The following estimates are based on the qualified soil groups allocated to the Department of Agriculture's soil-landscape mapping.

Table 14.1: Soils susceptible to subsurface compaction in the NAR (Department of Agriculture 2003)

Zone	Area of agricultural land (ha)	Soils with high subsurface compaction susceptibility	
Subregion		ha	%
Greenough	1,776,237	610,464	34.37
West Midlands	742,584	157,710	21.24
Moore River	1,279,578	495,628	38.73
Yarra Yarra	921,222	446,987	48.52
TOTAL	**4,719,621**	**1,710,788**	**36.25**

This analysis indicates that a large part of the NAR have soils with characteristics that make them susceptible to subsurface compaction, particularly the Greenough and Yarra Yarra where sandy soils and uniform coarse textured soils dominate.

Impacts

The main cause of subsoil compaction on tilled soils is wheeled vehicular traffic, especially heavy tractors. The amelioration of subsurface compaction can result in large yield increases according to Jarvis and Porritt (1985). Compaction can also occur due to trampling by stock, particularly on wet soils, and the development of plough pans. The principles of subsurface compaction are summarised by Needham *et al.* (1998).

Subsoil compaction influences plant growth by:

- decreasing soil pore size and continuity;
- decreasing root penetration and density;
- reducing access to moisture and nutrients; and
- predisposing the crop to waterlogging and to soil pathogens (Rengasamy 2000).

The effect of compaction on crop growth is complicated by different responses from various species and cultivars.

Management options

1. **Deep ripping (Recover):** Using deep cultivation to loosen subsurface layers. See page 124 of 'Soilguide' (Needham *et al.* 1998) for a decision tree on managing subsurface compaction using deep ripping.

2. **Tramline farming (Adapt):** Still in development. This has become a practical option due to availability of differential GPS and self-steering technology for paddock machinery. Also possible using manually steered equipment equipped with marker arms (Blackwell 1998).

3. **Stock control (Contain):** Defer grazing, reduce stocking rates or remove stock altogether from soils at risk, particularly when susceptible soils are wet (Needham *et al.* 1998).

Effectiveness

1. **Deep ripping** is good for all sorts of compacted soils. The key issue here is using gypsum along with deep ripping to re-aggregate the ripped soil. Deep ripping should not be recommended alone (Needham *et al.* 1998). On duplex soils where the top soil is > 30 cm deep the soil responds similarly to a uniform coarse textured soil. Were the A horizon is < 30 cm deep the subsoil properties may override any deep ripping effects (for the effect of deep ripping on duplex soil, see Hamza and Anderson 2002, 2003).

2. **Tramline farming:** Benefit relates to confining traffic to tramlines and avoiding compaction between the tramlines (Blackwell 1988). The confinement of compaction to tramlines has the benefit of increasing the effectiveness of deep ripping. Benefits also include reduced overlap and savings on inputs (Blackwell 1998).

3. **Stock control:** Effective when the soil is close to a lower plastic limit as it helps to reduce structural decline and can improve workability in following cropping years. Reduced stocking rates and deferred grazing have also been shown to help reduce the degree of structural damage to fragile surface soils (Needham, Moore and Scholz 1998).

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ISSUE 15: WATERLOGGING

Cause

Waterlogging is caused by three major pathways: (1) Surface water entering the soil profile quicker than it can infiltrate and drain, resulting in water ponding on the surface; (2) perched water caused by clay subsoil in duplex soils, preventing subsurface drainage in flat areas; and (3) deep water infiltration by groundwatertable rise or capillary action, which is associated with the development of salinity. Waterlogged conditions are accelerated by having the clay subsoil closer to the surface, having little infiltration pathways, such as tree roots, through clay or structureless soils and by having low hydraulic conductivity of sandy topsoils. Hydraulic conductivity is a physical property that allows water to infiltrate or rise by capillary action through the soil, where it evaporates at the surface, drying the soil profile (Hunt and Gilkes 1992). Waterlogging usually occurs in the permeable A soil horizon, that overlies an impermeable or slowly permeable B horizon (Moore and McFarlane 1992).

Extent

Waterlogging is most significant and frequent in areas of low relief that receive more than 400 mm annual rainfall. Many soils are only affected by subsoil waterlogging which is not readily visible and so the true extent of waterlogging is often underestimated. Although satellite imagery can be used to assess the extent of waterlogging in any given year, no comprehensive mapping throughout the agricultural area has been undertaken. The following estimates of waterlogging are based on the land units allocated to the Department of Agriculture's soil-landscape mapping;

Table 15.1: Waterlogging risk in the NAR (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Land with high to very high risk of waterlogging[1]		Land with moderate to very high risk of waterlogging[2]	
Hydrological zone		ha	%	ha	%
Greenough	1,776,237	10,331	0.58	64,225	3.62
West Midlands	742,584	17,401	2.34	41,727	5.62
Moore River	1,279,578	77,795	6.08	222,887	17.42
Yarra Yarra	921,222	32,468	3.52	155,224	16.85
TOTAL	**4,719,621**	**137,995**	**2.92**	**484,063**	**10.26**

1. Land with a high risk of waterlogging has watertables at 50 cm for 3-6 months in an average year. These figures include soils that are currently affected by waterlogging as well as soils affected by a combination of salinity and waterlogging.
2. Land with a moderate risk of waterlogging has watertables at 50 cm for 1-3 months in an average year. These figures include soils that are currently affected by waterlogging as well as soils affected by a combination of salinity and waterlogging.

Land with a high to very high waterlogging risk is minimal in the NAR. Land with a moderate to very high risk of waterlogging is more pronounced in the Moore River and Yarra Yarra subregions due to low relief valley floors and susceptible soils in these areas.

Impacts

The impacts of waterlogging are summarised on pages 155-157 of the 'South west Hydrological Information Package' (Tille *et al.* 2001), pages 96-97 of 'Soilguide' (Moore and McFarlane 1998) and Setter and Belford (1990).

Waterlogging can have major effects on crops, pastures and other plants because it deprives the roots of oxygen. Waterlogging:

- exacerbates the effects of salinity on plants;
- reduces crop and pasture productivity (and can lead to plant death);
- results in patchy crop performance;
- contributes to groundwater recharge;
- contributes to nutrient export;
- increases the risk of water erosion and flooding;
- increases the risk of soil structure decline;
- provides weed species with a competitive advantage;
- reduces the area suitable for horticultural development; and
- reduces trafficability of the land (machinery and vehicles get bogged).

Management options

Management options for waterlogging can often be implemented as part of an integrated package to combat salinity, flooding, water erosion and/or nutrient loss.

1. **High water use farming systems (Contain and Adapt):** Establishment of high water use pasture, crops and trees upslope to reduce recharge and waterlogging – see pages 111-121 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
2. **Tolerant crops and pastures (Adapt):** Establishment of crops and pastures with a tolerance to waterlogging – see pages 159-161 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
3. **Soil management (Recover and Contain):** Minimising tillage and applying gypsum to improve water percolation through profile.
4. **Shallow surface drains (Recover and Contain):** Installing spoon drains, spinner drains or W-drains to remove surface water – see page 162 of the 'South west Hydrological Information Package' (Tille *et al.* 2001) and McFarlane *et al.* (1990).
5. **Bedding and mounding (Contain):** Installing raised beds to lift plant roots above saturated soil – see page 162 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
6. **Interceptor drains and banks (Contain):** Constructing grade banks or seepage interceptor drains upslope from waterlogged areas to divert water away – see pages 163-164 of the 'South west Hydrological Information Package' (Tille *et al.* 2001) and McFarlane and Cox (1990).
7. **Deep open drains (Contain):** Constructing open drains (60-250 cm deep) to remove subsoil water – see page 165 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
8. **Subsoil drainage (Contain):** Installing shallow collector drains, mole channels or tube drains to open drains (60-250 cm deep) to remove subsoil water – see page 165 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).

Effectiveness

1. **High water use farming systems:** Can be effective in managing waterlogging caused by rising watertables in intermediate or local flow systems. Best used in conjunction with other management options.
2. **Tolerant crops and pastures:** Although this is primarily an adaptation rather than a control option, increased water use by plants on affected areas can lead to reduced waterlogging.
3. **Soil management:** Only applicable where waterlogging is due to surface ponding on otherwise well drained soils.
4. **Shallow surface drains:** Effective on heavy soils such as clays and shallow duplexes.
5. **Bedding and mounding:** Results from Bakker *et al.* (1999, 2001, 2002) show increased crop yields on raised beds.
6. **Interceptor drains and banks:** Effective on duplex soils where surface run-off or through flow in the topsoil is contributing to waterlogging downslope.
7. **Deep open drains:** Effectiveness can be highly variable depending on soil type, most effective on stable, highly permeable soils.
8. **Subsoil drainage:** Can be very effective but usually only really cost efficient in areas of intensive agriculture.

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ISSUE 16: WATER EROSION

Cause

Water erosion occurs in three phases; detachment, transport and deposition. Detachment is caused by rainfall, surface water flow, tillage and stock movements. Transport is influenced by soil structure stability, rainfall intensity, slope angle, slope length, management practices and amount of ground cover; which in turn influences the speed, volume and accumulative volume of water as run-off.

Raindrop impact is considered the main cause of surface soil detachment in sheet erosion. Rill erosion occurs in depressions and cultivation furrows, where the direct speed and force of flowing water overcomes the soil strength, causing detachment of particles. Gully erosion is caused by flowing water of greater volume, speed and force, sufficient to remove materials while creating a channel. Water movements through the soil profile causes tunnel erosion, where particles are carried away in solution, leaving behind tunnels that may eventually cave in. Water erosion selectively removes silts and clays from the profile, as these require less energy to move (Coles and Moore 1998).

Extent

The distribution of erosion is determined by the nature of the soils and landforms in conjunction with land management practices and seasonal climatic events. Sedimentation of dams, creeks and river systems is an associated problem and is a consequence of water erosion from the slopes above, causing the flow lines to become obstructed, which exacerbates flooding and salinity.

Erosion is also associated with areas affected by salinity and waterlogging. Once an area becomes salt affected it no longer sustains the plant growth that can protect the surface from raindrop impact and surface scouring by run-off. Since these areas are often close to or associated with natural drainage systems, the many tons of soil that are detached and transported into the waterways from this source, goes largely unnoticed.

Most erosion occurs in episodic events. While severe gully or rill erosion may leave long-term scars on the land surface, many forms of erosion are more gradual and less obvious. Sheet erosion may be observed during, and immediately after, a particular erosion event. However, the evidence has usually largely disappeared from the paddock surface by the following season. In the wheatbelt, erosion is most common below large rock outcrops, mallet hills and breakaways, especially on hardsetting loams or clays. The following estimates of erosion hazard are based on the land units allocated to the Department of Agriculture's soil-landscape mapping:

Table 16.1: Water erosion hazard in the NAR (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Soils with very high to extreme water erosion hazard[1]		Soils with high to extreme water erosion hazard[1]	
Subregion		**ha**	**%**	**ha**	**%**
Greenough	1,776,237	46,808	2.64	54,320	3.05
West Midlands	742,584	65,483	8.82	67,822	9.13
Moore River	1,279,578	16,923	1.32	44,641	3.49
Yarra Yarra	921,222	24,331	2.64	26,285	2.85
TOTAL	**4,719,621**	**153,545**	**3.25**	**193,067**	**4.09**

1. Land with a high risk of water erosion includes soils that are currently affected by waterlogging.

Table 16.1 shows that the NAR does not generally have a high risk of water erosion, apart from the West Midlands. Previous erosion events have been associated with episodic events such as severe thunderstorms or cyclonic rain-bearing depressions combined with inappropriate tillage practice or lack of surface water flow control systems, particularly in areas prone to water erosion such as sloping land.

Impacts

The impacts of water erosion are summarised on pages 183-184 of the 'South west Hydrological Information Package' (Tille *et al.* 2001) and pages 230-231 of 'Soilguide' (Coles and Moore 1998).

Water erosion:

- reduces soil fertility and productivity by removing fine clay and organic material;
- exposes problematic subsoils (e.g. sodic clays);
- results in sedimentation of dams and waterways;
- contributes to eutrophication of water bodies;
- reduces trafficability of paddocks; and
- can threaten infrastructure such as roads and fences.

Sheet and rill erosion are more common on steeper land that has been heavily grazed or cultivated over the spring and summer, leaving soils bare and exposed to erosion in the event of heavy summer or opening rain. Land within the hilly landscape of the NAR is most seriously affected by soil erosion where it is conventionally cultivated for grain or pasture production, especially in the higher rainfall areas. Land where sheep heavily graze and sheep tracks concentrate water are also a significant problem towards the end of the summer dry period. The most significant erosion events have occurred on land during the critical period before the opening rains where soils are bare, dry and loose due to cultivation or grazing. Similar problems are experienced on land early in the growing season, which has been cultivated (especially if heavy rain falls soon after cultivation and before pastures and crops emerge).

Management options

Management options for water erosion can often be implemented as part of an integrated package to also combat waterlogging, salinity, flooding, and wind erosion and/or nutrient loss. Management options for erosion problem areas are detailed on pages 240-242 of 'Soilguide' (Coles and Moore 1998).

1. **Farm layout (Recover and Contain):** Realigning fences, tracks, stock watering points, gateways and laneways to avoid channelling run-off and isolate areas of high erosion risk – see pages 186-187 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
2. **Maintaining vegetative cover (Recover):** Establishment of perennial vegetative cover, maximising productivity of annual crops, retention of stubble and trash in broadacre crops, use of cover crops, see pages 187 and 188 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).

3. **Stock control (Contain):** Managing grazing pressure so that paddocks are not denuded and soils are not disturbed by livestock when waterlogged or susceptible to erosion – see page 187 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
4. **Cross slope cultivation (Contain):** Cropping along the contour or at a slight gradient to slow run-off – see page 188 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
5. **Reduced tillage (Recover and Contain):** Implementing minimum tillage or no tillage cropping systems to maintain soil stability – see page 188 of the 'South west Hydrological Information Package' (Tille *et al.* 2001) and page 239 of 'Soilguide' (Coles and Moore 1998).
6. **Soil conservation earthworks (Recover and Contain):** Constructing contour sills, grade banks, broad based banks and interceptor drains to intercept run-off and effectively reduce slope length – see pages 189-193 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
7. **Waterways (Recover and Contain):** Using well-designed waterways to remove run-off safely – see page 194 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
8. **Gully control (Recover and Contain):** Using gully head sills, flumes, hay bales, drains and gully filling to control and rehabilitate erosion gullies – see page 194 of the 'South west Hydrological Information Package' (Tille *et al.* 2001).
9. **Reducing waterlogging (Recover and Contain):** Saturated soils are more prone to water erosion, so management options to reduce waterlogging can also reduce the risk of erosion.

Effectiveness

1. **Farm layout:** Essential for the effective management of water erosion.
2. **Maintaining vegetative cover:** Essential for the effective management of water erosion.
3. **Stock control:** Essential for the effective management of water erosion.
4. **Cross slope cultivation:** Important when cropping on slopes.
5. **Reduced tillage:** Very effective in reducing (but not eliminating) erosion in broadacre cropping areas.
6. **Soil conservation earthworks:** Essential, if earthworks are correctly designed and selected to match the land use, topography and soils.
7. **Waterways:** Well-designed and maintained grassed waterways are essential for disposing of excess water.
8. **Gully control:** Only applicable where gully formation has already started.
9. **Reducing waterlogging:** Can contribute to erosion control where waterlogging is a contributing factor.

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ISSUE 17: WIND EROSION

Cause

Wind erosion is caused by the shear force of air moving at erosive velocity (more than 8 m/s) over loose, dry soil with insufficient protection by trees, plants or plant residues. Dust can be picked up by air movements and carried high in the atmosphere before it is deposited, possibly thousands of kilometres away. The aerodynamic uplift of wind has to overcome the force of gravity and cohesion between soil particles. Fine sand particles of 0.1 mm in diameter are the most erodible, as they are light enough to lift and large enough to be captured by aerodynamic forces. A small amount of soil moisture would obtain sufficient cohesion, reducing the soil's erodibility.

Saltation, suspension, surface creep and deposition are the four mechanisms of wind erosion. Saltation occurs where the velocity of the wind picks up particles and carries them a short distance. When the particles land, energy is transferred to the next particle which triggers their saltation, accelerating the movement of soil downwind until either the wind is reduced or a barrier is reached. Suspension is caused by either saltation bombardment, when clays and silts are dislodged upon impact, or are lifted by wind while saltation particles are airborne. Particles smaller than 50 μm are not easily lifted by wind as they are too small, but are light enough to remain suspended and be carried. Saltation also causes other particles to roll, particularly particles larger than 0.5 mm that are unable to be lifted and thus roll along the surface, called surface creep. Deposition occurs where the winds are reduced below a level to initiate saltation or sustain suspension.

Wind erosion does not occur where the soil is protected by adequate ground cover. Elements of roughness such as trees, stubble and large soil aggregates, clods and rocks reduce wind speed at the surface by friction so that it is not of erosive velocity. As a guide, 30 per cent cover of standing stubble will minimise erosion, while 50 per cent cover is recommended for prostrate stubbles (Moore *et al.* 1998).

Extent

Wind erosion is most common on loose, coarse, dry surface soils (most typically sandy soils) in landscape positions exposed to strong winds (such as crests).

Most erosion occurs in episodic events. Evidence of wind erosion may be observed during, and immediately after, a particular erosion event. However, the evidence is usually much less clear by the following season. For these reasons it is very difficult to make any meaningful measurement of the current extent of erosion. The following estimates of wind erosion hazard are based on the land units allocated to the Department of Agriculture's soil-landscape mapping.

Table 17.1: Wind erosion hazard in the NAR (Department of Agriculture 2003)

Zone	Area of private agricultural land (ha)	Soils with very high to extreme wind erosion susceptibility		Soils with high to extreme wind erosion susceptibility	
Subregion		**ha**	**%**	**ha**	**%**
Greenough	1,776,237	212,644	11.97	906,579	51.04
West Midlands	742,584	83,532	11.24	530,523	71.44
Moore River	1,279,578	103,733	8.11	551,144	43.07
Yarra Yarra	921,222	52,157	5.66	189,628	20.58
TOTAL	**4,719,621**	**452,066**	**9.58**	**2,177,875**	**46.15**

Very high to extreme wind erosion susceptibility is particularly an issue in the Greenough and West Midlands in areas dominated by sandy soils, which are highly susceptible to wind erosion, especially during periods of drought and in late summer.

Impacts

Wind erosion has long been recognised as a major land degradation risk in Western Australia. The environmental and agricultural impacts of wind erosion can include the following (*from Moore *et al.* (1998) and Penny (1999)):

- loss of soil;
- loss of macro and micro nutrients;
- long-term loss of productivity;
- loss of pasture seed bank;
- atmospheric pollution;
- sand blasting damage to crops;
- a reduction in rooting depth;
- soil structure decline;
- an increase in the mortality of newborn sheep and recently shorn sheep; and
- sand drift around fences.

Land management and the amount of ground cover play a major role in determining the amount of erosion that occurs during strong winds. Wind erosion is exacerbated during periods of drought.

Management options

Wind erosion can be managed either by strategies aimed at reducing wind speed below the threshold or by reducing the amount of exposed loose soil (Penny 1999).

1. **Windbreaks (Contain):** Tree belts have been demonstrated to reduce wind erosion risk (Cleugh 2003)
2. **Maintain at least 50 per cent vegetative cover (Recover and Contain):** Adjust land use practices so that ground cover is maintained at above 50 per cent for susceptible soils.

Management strategies (namely winter cropping and summer grazing) that can help achieve this are summarised by Carter (1996), Carter (2002) and Findlater and Riethmuller (1993).

3. **Problem area management (Contain):** If the susceptibility of a paddock varies widely, fence to soil type, so that susceptible areas can be managed separately.
4. **Management of livestock (Recover):** Ensuring farm layout is such that watering points, gateways, feedlots, etc. are not sited on susceptible soil types.

Effectiveness

1. **Windbreaks:** Can be effective, although it is unlikely that sufficient belts of trees could be planted to provide complete control. Generally used in conjunction with other management systems.
2. **Maintain at least 50 per cent vegetative cover:** Effective. Relies on the monitoring of the wind erosion risk of paddocks and adjusting land use practices (e.g. destocking). Seasonal conditions (such as drought) can make it difficult to maintain ground cover at adequate levels.
3. **Problem area management:** Effective. Most likely to occur where there is a small area that is limiting management options for a larger paddock. A recent development is claying soil to reduce the wind erosion risk.
4. **Management of livestock:** Is effective if numerous entry and exit points to paddocks are established and water points are duplicated across paddocks. This could be combined with feeding of stock (when required) close to preferred water point locations to encourage usage.

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ISSUE 18: SOIL CONTAMINATION

Cause

Soil contamination results from spilling, burying, or migration of deposited hazardous substances. Sources of migrating hazardous substances could be from water run-off or leaching from contaminated sites. Some previously accepted and current agricultural practices involve the use of hazardous substances, such as herbicides, pesticides and fertilisers (US EPA 2004).

Organochlorines, including DDT (Dichlorodiphenyltrichloroethane), were used as a pesticide control in orchards, potato crops, backyard vegetable patches and during the Argentine Ant eradication campaign (Ambrose 2000a). Organochlorines were banned in 1987 as part of the Commonwealth, States and Territory Governments' and meat industry's integrated action plan to reduce the risk of organochlorines in beef (draft version of Animal health in Australia, 1994). (The half-life of the most commonly used OCs are 10 to 50 years for DDT and dieldrin, and 7-10 years for heptachlor and chlordane, thus it is likely that OC compounds remain in the environment (Ambrose 2000b).)

On-farm contamination sources related to current agricultural practices include chemicals, fertilisers, petroleum products and animal wastes (Mingenew Irwin Group 2004). Some contaminants from previously accepted practices break down slowly and may still persist in the environment, as listed in Table 18.1.

Table 18.1: Potential contaminants and their sources (Source: Diment 2003)

Residue source	Contaminant	Original use
Dump sites	Lead, organochlorines, mercury	Paint tins, batteries
Farm sheds	Lead, mercury, dieldrin	Batteries, termite treatment
Wooden yards	Dieldrin and DDT	Termite treatments
Old dips and shower sites	Dieldrin, arsenic	Parasite treatments
Power poles	Dieldrin	Termite treatment
Old wooden buildings	Dieldrin and DDT	Termite treatment
Silos	Mercury, dieldrin	Pest treatments
Chemical storage area	All residual chemicals	Old leaking tins, drums
Old orchards	Dieldrin, DDT	Butt spray for pests
Fertiliser site	Cadmium	Crop and soil applications

Extent

There is little known about the extent of soil contamination in the NAR, but the issue had been raised by a few members in the community. Land likely at risk of OCs are areas used prior to 1987 for horticultural production, broadacre cropping or had buildings and other structures such as power poles, where OCs would have been used as pesticides. The extent of OC accumulation in animals grazing is determined by soil type, pasture length, season, type of pasture, root structure of plants, subterranean clover, the period of exposure, contaminant present and level of contamination. Soils need to be tested to determine the extent of contaminants if present and the results may still not reflect the true extent as contaminants may be unevenly distributed (Dixon, Diment and Ambrose 2000).

Impacts

Contaminants can adversely impact on the health of plants when they are taken up by the roots, and on animals and humans if the soil in ingested or inhaled. However, impacts are highly dependent on the nature, extent and residual time of the contaminant (US EPA 2004). Only a short amount of time is needed for a grazing animal to build up OCs to a level exceeding the Australian Maximum Residue Limit (MRL) for human consumption of 0.2 ppm (Dixon, Diment and Ambrose 2000).

Worldwide banning of DDT occurred after concerns became evident on its detrimental effects on wildlife. Some countries continue to use DDT for the control of malaria carrying mosquitoes. Concerns exist over its persistence in the environment, bioaccumulation and possible carcinogenic properties.

Management options

The Australian National Residue Survey (NRS) program is the Primary Monitoring Program carried out for both the Commonwealth and State governments, responsible for safeguarding the health of consumers from agricultural products. Producers are responsible for the quality assurance of their products and are recommended to identify and contain potential contamination sources to prevent exposure to livestock.

Management at the farm level is required to prevent sheep products with residues above the MRL from entering the food and fibre chain. Producers should follow the instructions on chemical labels, to ensure the correct withholding period is carried out. The withholding period is a minimum time between the application of a chemical and when the animal, crop or pasture is slaughtered, harvested or grazed. This is a legal requirement imposed when chemicals are registered and is the time required to ensure MRLs are not exceeded (Dixon 2001).

Best Management Practices recommended by ChemCert, 2000 are summarised below:

- *General*
  - Ensure fuel, chemicals and fertilisers are transported and handled safely (in accordance to State and Federal laws).
  - Report any spill or possible source of contamination to the local government authority.
- *Fertilisers*
  - Do not store fertilisers in heaps within paddocks (always store on sealed pad and under cover).
  - Soil test regularly and apply only the required amount of fertilisers, which should not be spread before significant rainfall events to reduce spread of contamination to waterways.
- *Pesticides*
  - Use pesticides only when necessary.
  - Minimise spray drift through adjusting drop size and boom height and leaving buffer zones around waterways. Do not spray pesticides with rain impending.
  - Follow instructions on labels carefully, particularly recommended rates and withholding periods.

  - Always dispose of chemicals and containers in accordance with label instructions.
  - Store pesticides in lockable sheds with sealed bases.
  - Do not locate storage sheds on floodplains.
- *Petroleum products*
  - Ensure fuel storage does not leak, check regularly.
  - Fuel storage in confined area and on a sealed base (gravel, concrete, etc.).

There are three general approaches to clean up localised contaminated soil. These are:

- excavation, treating and disposal,
- treating of soil 'in situ', or
- containment of the soil to prevent further spread (US EPA 2004).

Effectiveness

The appropriateness of the management option adopted depends on the nature of the contaminant, extent and severity of impact on the environment and the likelihood of the contaminant spreading (US EPA 2004). Correct use and disposal of chemicals can minimise the risk to markets and exports of agricultural products by allowing chemical residues to subside before exposure (Dixon 2001).

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ISSUE 19: SOIL BIOLOGICAL ACTIVITY

Importance

Soil dwelling flora and fauna exist on organic material and on other soil organisms. They play critical roles in decomposition of organic matter, mineralisation and fixation of nutrients, assisting plant uptake of nutrients, degrading toxic substances, pedogenesis, soil carbon sequestration and greenhouse gas emission. Beneficial organisms also reduce the incidences of soil pathogens and plant diseases and are used to clean up contaminated sites through a process known as 'bioremediation'. These roles are not just essential to natural ecosystems by also for the sustainable management of agricultural systems (Convention on Biological Diversity 2001). It is claimed that well managed soils, with adequate organic matter supporting biological activity, is more resilient to land degradation issues (McCoy 2002). Functional groups of soil biota are listed in Table 19.1, from Bunning and Jimenez (2003).

Table 19.1: Effects of different functional groups on soil function (Source: Bunning and Jimenez 2003)

Functional group	Soil function
Roots	Aggregation, porosity, water and nutrient cycles, plant production, soil organic matter availability, soil biological activity
Ecosystem engineers (e.g. termites, ants and earthworms)	Bioturbation producing biogenic structures (regulating soil physical properties and processes), affecting soil organic matter dynamics, nutrient cycling, soil biological activity
Litter transformers (macro- and micro- arthropods, enchytraeids, other detritus feeders)	Nutrient mineralisation, organic matter protection and decomposition (some bioturbation)
Phytophages and plant parasites	Some bioturbation
Micropredator food web (e.g. nematodes and protozoa)	Nutrient mineralisation
Microflora: Symbionts, plant growth promoters, pathogens, nutrient cycles, biocontrol agents	Aggregation, decomposition rates, biodegradation of toxic material, nutrients cycles and availability, biocontrol

Bacteria and fungi are responsible for most of the mineralisation of organic matter. Enzymes are released by micro-organisms, which oxidise organic matter in return for energy and carbon that are released from the oxidation reaction. The end product of mineralisation is the inorganic form of nutrients, vital for plant uptake (Soilhealth.com 2001). Nitrifying bacteria play an important role in converting ammonia into nitrate, at optimal temperatures 26-32°C, when the carbon:nitrogen ratio is low–medium with adequate moisture availability. Denitrifying bacteria, on the other hand, convert nitrates to gaseous nitrogen and nitrous oxide, which is released to the atmosphere. These bacteria are likely to dominate poorly-drained, waterlogged soils, where conditions are anaerobic (Peet 2004 and Soilhealth.com 2001).

Pathogenic organisms usually exist in soils in low numbers, but cause disease in susceptible plants when conditions favour their growth and survival. Beneficial soil organisms are known to biologically control pathogenic organisms (Soilhealth.com 2001). In Australia, *Rhizoctonia solani* (root rot disease) caused less damage to wheat seedlings when earthworms were present. Mechanical soil disturbance also reduces disease severity, and it is possible that the physical mixing of soil by the worms reduces pathogen severity. The presence of earthworms also enhanced the movement and colonisation of wheat roots by biologically controlling the bacteria pathogen *Pseudomonas corrugata* (Peet 1995).

Extent

The status of soil health in the NAR is not well known and is speculated to be very poor in relation to soil biological activity. It is suggested that key indicator species (e.g. earthworms) to reflect functional groups, or measuring respiration, C fluxes and nutrient balances to determine the activity of soil biological organisms. Visible indicators such as earthworms, insects and moulds as well as the biogenic structures they produce, such as burrows, earthworm casts, termite mounds, *Rhizobium* nodules are comprehensible and useful to farmers and other land managers. Problems with these indicators include variation in spatial heterogeneity and unpredictable interactions with soil organisms and climate variability (Bunning and Jimenez 2003).

Staff from the Soil Biology Research Group at the University of Western Australia are currently developing a package of indicators that will be relevant to Western Australian conditions. The amounts of ATP and specific enzymes in soil also indicate how many organisms are in the soil (Soilhealth.com 2001).

Impacts

Agricultural developments have become increasingly reliant upon cultivation, harvesting, high yielding varieties and excessive use of fertilisers and pesticides. These practices have largely replaced the functions provided by soil organisms on an intensified scale. Should all the organisms from a single functional group, listed in Table 19.1, become absent from a system, the system would be clearly affected (Bunning and Jimenez 2003).

The exact impact of farming practices on soil biological activity is poorly understood in the NAR. It is speculated the use of pesticides, herbicides and burning and tillage practices must have significant impacts on soil biological activity. This concern has also been raised by a few community members of the NAR.

Management options

There is limited information on the impacts of farming practices. Soil biological activity is known to occur at healthy levels when the conditions are optimal, i.e. carbon: nutrient ratios of organic matter, moisture availability, oxygen availability and temperature.

The interaction of biological components of soil is very complex. Further research is needed to develop a better understanding of these components to be able to manage the effects of agricultural practices. Ten management guidelines outlined in Soilhealth.com (2001) are as follows:

- Soil erosion should be controlled to minimise loss of soil organisms.
- Plant organic matter should be retained to maximise nutrient cycling and soil aggregation processes.
- Some disturbance of soil is necessary to maximise soil biological diversity.
- Nitrogen fixing bacteria should be selected that match the host, soil characteristics (such as pH) and environmental conditions.
- Inputs of nitrogen fertiliser should be calculated to complement nitrogen cycling from organic matter.

- Inputs of phosphorus fertiliser should be calculated to complement and enhance the activities of arbuscular mycorrhizal fungi.
- Any substance added to soil should be assessed in terms of its effects on soil biological processes and soil biological diversity.
- Crop rotations and tillage practices should be selected to avoid development of soil conditions that enhance the growth and survival of plant pathogens.
- The capacity of a management practice to produce a commercial product should be considered in parallel with its capacity to maintain and/or increase soil biological fertility.
- Sufficient time should be allowed for establishment or restoration of a level of soil biological fertility appropriate for particular soils and land management.

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APPENDIX 1

NRM THREAT PRIORITIES FOR THE NORTHERN AGRICULTURAL REGION

NRM issues for the Northern Agricultural Region have been assessed using two methodologies, that both essentially take into account the timing and scale of impact of issues and relative feasibility and ease of management options. The Department of Agriculture's process is based on a value versus threat matrix using the methodology developed during the Salinity Investment Framework (SIF) process. The issues are further assessed by weighting them according to private/public benefit and availability of technology/procedures to ameliorate the issue. The value versus threat matrix determines the relative priority of assets and soil-landscape zones for each asset, defined by the Tier that they fall under, as shown in Figure 1.

A Natural Resource Management Issues Database was developed by the Department of Agriculture, which contained information on threats and values in the spatial framework of *soil-landscape zones*, as defined by the Natural Resources Assessment Group of the Department of Agriculture. There are 31 zones described for south-western Australia, nine of which fall within the Northern Agricultural Region.

The threat to the asset was determined using a combination of expert knowledge and the known physical qualities of the land resource as defined by land resource assessment information collected by DAWA and stored in agency databases. The timing of impact and impact scale of relevant processes were assessed, as described in Table 1. The value of the asset is based on the average value of agricultural land ($/ha) determined from year 2000 BankWest data. Other methods for assessing value are possible. These include using the gross value of production, or more importantly an assessment of the ecological value of the asset by taking into consideration non-production values. In addition issues such as the feasibility and cost of managing the threatening process need to be considered. The threat-value tables for the agricultural land asset for the south-west, therefore only give a broad comparative assessment of the issues facing various zones within south-western WA, and needs to be interpreted at that level (Department of Agriculture, CALM, Environment and Fisheries 2003).

Asset - Threat Class		Value of asset		
		High	Medium	Low
Threat	High	1st Tier		
	Moderate		2nd Tier	
	Low			3rd Tier

Figure 1. Value versus Threat Matrix and the Tiers that determine relative priority of asset classes. (Department of Agriculture, CALM, Environment and Fisheries 2003)

Table 1. Categories for assessment of land resource threats (Source: Schoknecht, unpublished)

Threat category	**Description**
HIGH	Current/imminent risk of high impact
MODERATE	Current/imminent risk of moderate impact OR Medium-term risk of high impact
LOW	Current/imminent risk of low OR Medium-term risk of low-moderate impact OR Long-term risk of low-high impact
Definition of terms	
Current/imminent (within 0-20 yrs)	High Impact (majority of asset at risk)
Medium-term (within 20-75 yrs)	Moderate impact (some of asset at risk)
Long-term (greater than 75 yrs)	Low impact (minority of asset at risk)

Table 2. Agricultural land asset: Priority ranking of Natural Resource Management issues over the nine Soil-Landscape Zones in the Northern Agricultural Region and for the regional average (based on the NRM Issues Database - Department of Agriculture Western Australia)

Resource threat	NAR average	221 Geraldton Coastal Zone	222 Dandaragan Plateau Zone	223 Victoria Plateau Zone	224 Arrowsmith Zone	225 Chapman Zone	226 Lockier Zone	231 Port Gregory Coastal Zone	Kalbarri Sandplain Zone	Irwin River Zone
Wind erosion	H	H	H	H	H	H	M	M	M	M
Ag. nutrient export	M	H	M	M	M	M	M	M	M	L
Animal (feral) sp.	M	M	M	M	M	M	M	M	M	H
Diseases (animal)	M	M	M	M	M	M	M	M	M	M
Irrigation water management	M	M	M	M	M	M	M	L	L	L
Loss of native veg. - salinity	M	L	L	M	M	M	M	M	L	L
Plant (weed) sp.	M	M	M	M	M	M	M	M	M	M
Soil health	M	M	M	M	M	M	M	M	M	M
Soil structure decline/compaction	M	L	M	M	L	M	M	L	M	L
Subsurface and subsoil acidification	M	L	M	M	M	M	M	M	M	L
Water erosion	M	L	M	M	L	M	M	M	L	L
Acid sulfate soils	L	L	L	L	L	L	L	L	L	L
Damage to infrastructure	L	L	L	M	L	L	M	L	L	L
Groundwater management	L	L	L	L	L	L	L	L	L	L
Land salinisation	L	L	M	M	L	M	M	L	L	L
Loss of native veg. - clearing	L	M	M	L	H	L	L	L	L	L
Protection of prime ag. land	L	H	H	L	M	L	L	L	L	L
Surface water supply	L	L	L	H	L	L	L	L	L	H
Water repellence	L	L	M	M	M	L	L	L	L	L
Waterlogging/ inundation	L	L	L	L	L	L	L	L	L	L

The second method for prioritising NRM issues was developed by the Northern Agricultural Catchment Council (NACC), which was based on principles used in the Nature Conservacy 5-S Framework for Site Conservation Spreadsheet (Nature Conservacy 2000). This methodology relies on expert knowledge for where information is poor and assumptions are made on known trends and modelling. Any decisions made on prioritisation at a regional scale needs to be further tested at higher resolution scales (Ubter, unpublished). The final process developed by the SIF will determine the amount and nature of information required for decision making (Department of Agriculture, CALM, Environment and Fisheries 2003).

The ‘Threat Ranker’ takes into account four dimensions, which can be further assessed by indicating a confidence level, as described in Table 3. The ranking is based on current impacts and does not necessarily highlight precautionary management to prevent future impacts, particularly for climate change (Ubter 2004). Threat ranking results are displayed in Figure 2.

Table 3. Threat ranking criteria, which are assigned a score upon which threats are ranked

Assessment type	Scale	Categories	Description
Current scale of threatening process	5	Very high	The threat is likely to be very widespread or pervasive in its scope.
	4	High	The threat is likely to be widespread and affect much of the asset.
	3	Medium	The threat is likely to be localised in its scope, and affect some of the asset.
	2	Low	The threat is likely to be very small and affect a limited proportion of the asset.
	1	None	There is no threat to the asset.
Severity of current impact	5	Very high	The threat is likely to destroy or eliminate the asset.
	4	High	The threat is likely to seriously degrade the asset.
	3	Medium	The threat is likely to moderately degrade the asset.
	2	Low	The threat is likely to only slightly impair the asset.
	1	None	There is no threat affecting the asset.
Time frame of the current impact	5	Very high	The pressure occurs constantly creating ongoing stress to the asset and reduces the condition of the asset OR the pressure occurs at a temporal rate at which the system is not adapted to respond OR the threat spreads at a fast rate over the geographic distance.
	4	High	The pressure occurs frequently reducing the condition of the asset over time. The threat spreads quickly.
	3	Medium	The pressure occurs infrequently and allows minimal time for the asset to recover/improve condition. The threat spreads at a medium rate.
	2	Low	The pressure occurs infrequently allowing the asset to respond/improve condition over time.
	1	None	The pressure occurs at a rate, which does not reduce the asset condition or ability to recover over time.
Feasibility of managing the threatening process	Technical knowledge (High/Med/Low)		The current level of technical knowledge to be able to manage the impact of the threatening process.
	Capacity to manage (High/Med/Low)		The feasibility in terms of resources and capacity to manage the impact of the threatening process.
	Willingness to deal (High/Med/Low)		The perceived willingness of social and political communities to undertake management of threatening processes.
Confidence level	0 - 1.0	NA	Confidence level is set to reflect the confidence of baseline data for which scale, severity and time frame have been set.

Area: NACC NRM Region
Asset: Agricultural Land

Scale, Severity and Time frame of Threatening Process

	Threat Class	Root Cause	Current Scale of Threatening Process		Severity of Current Impact		Timeframe of Current Impact		Score	Rank	Confidence Level	Comment
1	Acid Groundwater	Groundwater system near weathering granite - ferrolysis	Low	2 Low	Low	2 Low	Medium	3 Medium	7	15	0.2	Bores in NAR have not been monitored for acidity as yet
2	Acid Sulfate Soils	Naturally contain pyrite - reacts with exposure to O2	Low	2 Low	Low	2 Low	Medium	3 Medium	7	15	0.2	The existence of potential acid sulfate soils in the NAR is poorly understood
3	Biosecurity	Deliberate or accidental introduction	Very High	5 Very High	High	4 High	High	4 High	13	1	0.8	DoA - A Draft NRM Biosecurity Strategy has been developed for the SAR, but not yet for the NAR
4	Climate Change	Natural causes & increased greenhouse gases	Medium	3 Medium	Medium	3 Medium	Medium	3 Medium	9	9	0.6	DoA - The effect of global warming on Agriculture is not well understood, with models still largely subjective
5	Dryland Salinity	Removal of deep rooted perennials - Rising groundwater	High	4 High	High	4 High	High	4 High	12	2	0.8	Currently baseline data from Land Monitor is subjective, with underestimation of sandplain and hill side seeps. Views are based on 100yrs of research
6	Flooding	Intense rainfall with accumulation from water shedding areas	Low	2 Low	Medium	3 Medium	Medium	3 Medium	8	12	0.8	DoA Soil-Landscape mapping determines flood hazard. No consistent mapping of flooding events or prone areas have occurred
7	Herbicide Resistance	Selection pressure exerted by continuous use of herbicides	High	4 High	High	4 High	High	4 High	12	2	0.7	DoA - No comprehensive data. Reliance on expert knowledge of the region, with known areas of sandplain farming systems & STEP modelling
8	Non-wetting (water repellency)	Coarse grained soils covered by natural hydrophobic materials	Medium	3 Medium	Medium	3 Medium	Medium	3 Medium	9	9	0.9	DoA Soil-Landscape mapping - estimates on susceptible soil groups. Actual extent has not been measured. Based on processes and management research
9	Nutrient Loss and Eutrophication	Leaching, erosion & export of catchment soils	Low	2 Low	Low	2 Low	Low	2 Low	6	17	0.6	DoA Soil-Landscape mapping - estimates areas potential to export P, in absence of comprehensive soil, landuse, topographical and hydrological data. Little info in NAR
10	Remnant Vegetation Decline	Clearing, agriculture, grazing, industries & land deg. (habitat)	High	4 High	High	4 High	Medium	3 Medium	11	4	0.8	Info from DoA West Midlands Catchment Appraisal, Land Monitor quantifies actual extent
11	Soil Acidity	Nitrate leaching, removal of harvest material & weathering	High	4 High	Medium	3 Medium	Medium	3 Medium	10	5	0.8	DoA Soil-Landscape mapping - estimates soils at risk due to texture. Sandy soils have low capacity to buffer pH change
12	Soil Fertility Decline	Continual Ag. production & export by erosion & leaching	Medium	3 Medium	Low	2 Low	Medium	3 Medium	8	12	0.6	Generalised assessments of farm gate nutrient balance
13	Soil Structure Decline	Sodicity, cultivation & compaction	Medium	3 Medium	High	4 High	Medium	3 Medium	10	5	0.7	DoA Soil-Landscape mapping - based mostly on surface soil texture
14	Subsurface Compaction	Cultivating machinery & livestock, poor soil structures	High	4 High	Medium	3 Medium	Medium	3 Medium	10	5	0.7	DoA Soil-Landscape mapping - No comprehensive data on extent - based on estimates of susceptible soil groups
15	Waterlogging	Slow infiltration, clay subsoil & groundwater rise	Low	2 Low	Medium	3 Medium	Medium	3 Medium	8	12	0.7	DoA Soil-Landscape mapping - No comprehensive mapping undertaken - based on estimates from land units & low relief
16	Water Erosion	Poor soil stabilising structures (veg.) & fast moving water	Low	2 Low	High	4 High	Medium	3 Medium	9	9	0.7	DoA Soil-Landscape mapping - estimates hazard areas. Most occurs in episodic events and areas affected by salinity & waterlogging
17	Wind Erosion	Lack of groundcover protection	High	4 High	Medium	3 Medium	Medium	3 Medium	10	5	0.9	DoA Soil - Landscape mapping - estimates hazard areas. Most occurs in episodic events. Largely dependent on management of soil cover

Feasibility of Managing the Threatening Process

	Technical Knowledge of Managing Impact		Logistical Capacity for Managing Impact		Willingness to Manage Impact (Social, Political)		Score	Rank
1	Low	3 Low	Low	3 Low	Medium	2 Medium	8	15
2	Low	3 Low	Low	3 Low	Low	3 Low	9	16
3	High	1 High	Medium	2 Medium	Medium	2 Medium	5	3
4	Low	3 Low	Low	3 Low	Low	3 Low	9	16
5	Medium	2 Medium	Medium	2 Medium	High	1 High	5	3
6	Medium	2 Medium	Medium	2 Medium	Low	3 Low	7	12
7	Medium	2 Medium	Medium	2 Medium	High	1 High	5	3
8	High	1 High	Medium	2 Medium	Medium	2 Medium	5	3
9	Low	3 Low	Medium	2 Medium	Medium	2 Medium	7	12
10	High	1 High	High	1 High	Low	3 Low	5	3
11	High	1 High	Medium	2 Medium	Medium	2 Medium	5	3
12	High	1 High	High	1 High	High	1 High	3	1
13	Medium	2 Medium	Low	3 Low	Medium	2 Medium	7	12
14	Medium	2 Medium	Medium	2 Medium	Medium	2 Medium	6	10
15	Medium	2 Medium	Medium	2 Medium	Medium	2 Medium	6	10
16	High	1 High	High	1 High	Medium	2 Medium	4	2
17	High	1 High	Medium	2 Medium	Medium	2 Medium	5	3

Figure 2. Threat ranking for the Northern Agricultural Region, determined from NACC's 'Threat Ranker', resulting from an aggregation of scores by members of the NAR ARM team.

Ranking has been applied so far to individual assets, however it may also be used to determine priorities between assets. The community engagement process, undertaken by NACC, highlighted the major issues and threatening processes, for which the outcomes were very similar to the threat ranking methodology. The threat ranker is a first pass at determining areas for management, that are most important to address threatening processes (Utber 2004).

The first threat assessment methodology regarded wind erosion as being the most significant threat in the region, with biosecurity, water erosion and soil condition rating as medium threats. In relation to the second threat assessment methodology; an average of threat ranking scores submitted resulted in biosecurity being regarded as the most significant threat in the region, followed by dryland salinity, remnant vegetation decline, herbicide resistance and wind erosion. The difference in results between the two methodologies may be attributed to the slightly different assessment criteria and the fact that a number of threats were not shared between the models, as well as the varying perception/understanding of the threats by those using each model.

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