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AUSTRALIAN AGRICULTURE ASSESSMENT 2001

National Land & Water Resources Audit

A program of the Natural Heritage Trust

VOLUME 1

NATIONAL LAND AND WATER RESOURCES AUDIT

Providing Australia-wide assessments

The National Land and Water Resources Audit (Audit) is facilitating improved natural resource management decision making by:

Providing a clear understanding of the status of, and changes in, the nation's land, vegetation and water resources and implications for their sustainable use.

Providing an interpretation of the costs and benefits (economic, environmental and social) of land and water resource change and any remedial actions.

Developing a national information system of compatible and readily accessible land and water data.

Producing national land and water (surface and groundwater) **assessments** as integrated components of the Audit.

Ensuring integration with, and **collaboration between**, other relevant initiatives.

Providing a framework for monitoring Australia's land and water resources in an ongoing and structured way.

In partnership with Commonwealth, and State and Territory agencies, and through its theme activities—Water Availability; Dryland Salinity; Native Vegetation; Rangeland Monitoring; Agricultural Productivity and Sustainability; Australians and Natural Resource Management; Catchments, Rivers and Estuaries Condition; and Information Management—the Audit has prepared:

Assessments of the status of and, where possible, recent changes in the condition of Australia's land, vegetation and water resources to assist decision makers achieve ecological sustainability. These assessments set a baseline or benchmark for monitoring change.

Integrated reports on the economic, environmental and social dimensions of land and water resource management, including recommendations for management activities.

Australian Natural Resources Atlas to provide internet-based access to integrated national, State and regional data and information on key natural resource issues.

Guidelines and protocols for assessing and monitoring the condition and management of Australia's land, vegetation and water resources.

This report presents the key findings for the Audit's Agricultural Productivity and Sustainability theme as:

> *Australian Agriculture Assessment 2001* reports on landscape processes, soil, nutrient and water movement and serves as a key input towards improved land and water resources management.

Australian Agriculture Assessment 2001 was prepared in partnership with CSIRO Land and Water, Australia's States and Territories and major agricultural industries.

AUSTRALIAN AGRICULTURE ASSESSMENT 2001

Volume 1

National Land & Water Resources Audit
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Disclaimer

We invite all interested people, both within and outside Government, to make use of the Audit's reports, information, its Atlas and products in whatever way meets their needs. We encourage you to discuss Audit findings with the various partners and contributors who have prepared this information. Partners and contributors are referenced in this report.

The Commonwealth accepts no responsibility for the accuracy or completeness of any material contained in this report and recommends that users exercise their own skill and care with respect to its use.

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National Land & Water Resources Audit
A program of the Natural Heritage Trust

Minister for Agriculture, Fisheries and Forestry
Parliament House
Canberra, ACT 2600

Minister for Environment and Heritage
Parliament House
Canberra, ACT 2600

Dear Ministers,

I have pleasure in presenting to you *Australian Agriculture Assessment 2001*—a report of the National Land and Water Resources Audit.

This assessment demonstrates first and foremost the role of partnerships in understanding and addressing natural resource management issues facing Australian agriculture. The assessment of soil acidity (for example) is based on the combined resources of the Australian fertiliser industry, soil scientists and government agencies. It includes data from the thousands of soil tests taken by farmers as part of their integrated farm management each year. Up to 24 million hectares of agricultural soils are highly acidic (some five times the area at risk from dryland salinity)—presenting significant on-farm productivity and management challenges.

To set the benchmark for improvements in agricultural practice this report:

- details the first comprehensive assessment of **water-borne erosion** and **sediment transport** for Australia's agricultural catchments and rivers, and highlights implications for soil, river and estuary management;
- details **river nutrient budgets** and changes in nutrients loads to our rivers;
- details changes to **landscape water and farm nutrient balances** and the implications for on-farm nutrient management;
- forecasts the extent and impact of **soil acidification** on agricultural soils and their productivity;
- details new soil information for **Australia's agricultural soils**;
- details **progress of agricultural industries** in meeting natural resource challenges; and
- details key components of **land condition monitoring** that could be used to report changes in the natural resource base and tracks progress in implementing improved practices.

This report highlights the long-term nature of natural resource processes such as soil acidity or nutrient and sediment movement down rivers. Meeting the twin goals of increased productivity and reduced off-farm impacts requires ongoing commitment to innovation and continuous improvement in farm practice. The assessment of industry natural resource management practice highlights agricultural industry ability to adapt, improve and innovate.

Australian Agriculture Assessment 2001 and the more detailed information in the Australian Natural Resources Atlas will prove invaluable to regional communities as they set priorities for activities under the National Action Plan for Salinity and Water Quality and the extension of the Natural Heritage Trust.

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The assessment also provides a framework and information for government, industry and science agencies to review programs and develop the policies required to deliver sustainable agricultural development in Australia. It identifies the monitoring activities that would provide information to track improvements in practice and resource condition, ensuring efficiencies in program delivery and maximising returns on investment.

The Audit Advisory Council commends this report and the *Australian Natural Resources Atlas* to you. It remains for Australian agriculture in partnership with industry groups, research and development agencies and government to keep this information up to date and use it for tracking progress and setting natural resource management priorities.

I am pleased to present this report to the Natural Heritage Trust Ministerial Board.

Yours sincerely,

Roy Green

Chair
National Land and Water Resources Audit Advisory Council
October 2001

SUMMARY

Natural resource challenges facing agriculture

Australian agriculture feeds the nation with a diverse range of produce, contributes $17.6 billion every year to export earnings as raw and processed products, and employs approximately 400 000 Australians—generating national and regional wealth.

Australia's natural resources underpin our agricultural industries. Climatic variability, largely infertile and highly erodible soils, the chemistry of those soils, their salt stores and pH are all key factors affecting sustained productivity.

Agricultural activities can be broadly grouped into:

- *produce quality*—covering issues of food safety, meeting market specifications, processing, marketing, selling and transport (not covered by the Audit);
- *production*—covering issues of rotations, enterprise mix, varieties and trends in yield performance; and
- *natural resource maintenance and protection*—covering issues of on-farm resource management and off-farm impacts.

On-farm practices link these activities and are crucial to delivering natural resource outcomes.

The Standing Committee of Agriculture in Australia defined sustainable agriculture as:

> '*the use of farming practices and systems which maintain or enhance the economic viability of agricultural production; the natural resource base; and other ecosystems, which are influenced by agricultural activities*'
>
> SCA 1991

The guiding principles for sustainable agriculture were stated as:

- farm productivity is sustained or enhanced over the long term;
- adverse impacts on the natural resource base of agricultural and associated ecosystems are ameliorated, minimised or avoided;
- residues resulting from the use of chemicals in agriculture are minimised;
- the net social benefit derived from agriculture is maximised; and
- farming systems are sufficiently flexible to manage risks associated with the vagaries of climate and markets.

These succinct definitions imply the need to manage agricultural systems to be both profitable and environmentally sound, through adoption of efficient and environmentally benign management practices.

Australian Agriculture Assessment 2001 objectives

To provide information to:

- understand the links between natural resource condition and production—to maximise sustainable agricultural production;
- document the condition of natural resources used in agriculture—to maintain and protect the natural resource base on which agriculture depends; and
- determine off-farm exports and fluxes of sediments, carbon and nutrients—for quantifying the off-farm impacts of agriculture on public resources, rivers and estuaries.

Australian Agriculture Assessment 2001 assessed key factors related to natural resource sustainability, including:

- soil loss off-farm and through our rivers to estuaries and marine environments through water-borne soil erosion;
- nutrient balance, incorporating an assessment of all inputs and outputs in the production cycle;
- soil chemistry—particularly pH and soil nutrient status; and
- transport and delivery of nutrients through regional river networks.

To underpin this assessment, the Audit has compiled Australia's first integrated soil properties information system (the **Australian Soil Resources Information System**) for agricultural landscapes as a framework for assessing condition, change and trends of change in agricultural landscapes, and to assist in managing soils.

Australian Agriculture Assessment 2001 should be read in conjunction with other Audit assessments:

- water balance and the onset of dryland salinity are covered in *Australian Dryland Salinity Assessment 2000* (NLWRA 2001a);
- water use and water use efficiency are covered in *Australian Water Resources Assessment 2000* (NLWRA 2001b);
- Australia's Rangelands are covered in *Tracking changes: Australian Collaborative Rangeland Information System* (NLWRA 2001c).

Impacts of land use on native vegetation, and catchments, rivers and estuaries are covered in separate Audit reports. A related report—*Australians and Natural Resource Management 2001*—details the economic benefits that agriculture delivers to the Australian economy and the costs of resource use, particularly off-farm.

Landscape nutrient balances

Agriculture has *doubled* the productive capacity of agricultural landscapes. This capacity is determined by changes in water and nutrient availability and was assessed by mapping modelled water, carbon and nutrients balances and distribution of the major stores and fluxes; and determining how stores and fluxes respond to changes in agricultural inputs.

Net primary productivity (a measure of plant biomass gain) is an integrated measure of the coupled water, carbon, nitrogen and phosphorus balances. Distribution broadly follows rainfall patterns and is also influenced by air dryness, light and agricultural inputs. Net primary productivity strongly controls carbon stores in plants, litter and soil. Net primary productivity averages 0.96 Gt of carbon each year for the Australian continent. Nearly 60 Gt of the total *continental* carbon is stored as plant biomass (45%) and soil carbon (55%).

Agricultural nutrient inputs have increased continental net primary productivity by 5%; the mineral nitrogen store by 13% and the mineral phosphorus store by 8%. These increases have occurred over less than a quarter of the continent (since more than 75% of Australia is rangelands, national parks, or other largely natural and intact vegetation). Addition of nutrients and the use of legumes and irrigation water has increased agricultural productivity, nearly doubling pre-European stores of carbon, organic nitrogen and organic phosphorus. Soil mineral nitrogen, plant-available phosphorus, and nitrogen and phosphorus concentrations in soil water have also increased by up to a factor of five. These increases are concentrated in southern agricultural regions of Australia.

Harvested product is relatively small component of the continental net primary productivity and landscape stores of carbon, nitrogen and phosphorus. Nutrients applied to agricultural landscapes can exceed those required to achieve optimum production levels and in some regions are approaching diminishing returns. Attention to nutrient balance on farm will lead to more cost-efficient agriculture and fewer off-farm impacts.

Nutrients leaking from farms can lead to enriched rivers, estuaries and nearshore marine zones. Priority needs to be given to managing farm nutrient inputs more efficiently to counter increasing associated environmental costs.

Farm-gate nutrient balance

Nutrient management is a critically important issue for Australian agriculture. A balanced supply of all essential plant nutrients is required to sustain productivity and maintain soil fertility status on farm. Nutrient leakages off-site (especially nitrogen and phosphorus) can degrade the quality of water resources with enrichment of waterways leading to problems such as algal blooms.

In the higher rainfall, more intensively managed areas, Australia's surface soils have become more fertile following a long history of fertiliser application, but areas of soils with potentially low or marginal soil phosphorus, sulfur and potassium levels occur within the agricultural zone of all States. Australian soils are generally well endowed with calcium and magnesium.

A major shift in fertiliser consumption in Australia occurred during the 1990s, with a doubling of nitrogenous fertiliser use. The reasons for this upsurge is most likely associated with a range of factors including:

- higher nitrogen demands in more intensively cropped rotations;
- failure of pasture legumes to persist;
- varietal changes and adoption of minimum tillage practices;
- as a result of declining protein levels in wheat a growing awareness by farmers of the increased quality and yields obtainable from increased fertiliser applications; and
- the introduction of premium prices for higher protein wheat.

Farm-gate nutrient balances differ across Australia's regions. Balances for nitrogen, phosphorus, sulfur, and calcium are mainly neutral (inputs = exports) or moderately positive (inputs > exports) across much of the southern agricultural zone. At the gross regional farming scale, this suggests that levels of these nutrients are generally being maintained in soils. Potassium and magnesium balances are usually negative (inputs < exports) indicating that soil reserves are being progressively depleted.

In intensive industries with high nutrient use, such as sugar cane, dairying and horticulture, nitrogen and phosphorus balances were assessed as positive (inputs > exports). Highly positive (inputs > exports) nutrient balance indicate a likelihood that nutrients are moving off-farm to streams and groundwater.

Mainly negative nutrient balances were derived for the subtropical regions, suggesting nutrient depletion is occurring on these soils, many of which are naturally fertile. This implies that close attention to nutrient status needs to be maintained from a productivity perspective, so that soils retain their nutrient status.

Overall, attention needs to continue to be paid at a higher level in Australian agriculture to nutrient status, monitoring and tracking changes in all farming systems. This needs to be done with dual objectives—maximising yields on-farm and minimising export of nutrients off-farm, with the consequent impacts on the quality of water bodies.

Soil acidity

Soil acidification looms as a major soil degradation issue in all Australian States. The Audit estimates that 50 million and 23 million hectares of Australia's agricultural zone are already experiencing impacts from soil acidity in surface and subsoil layers respectively and that these are probably markedly affecting yields. Large areas of acidic soils occur in New South Wales, Western Australia, Victoria, and Tasmania.

Farmer awareness of the insidious nature of this issue has been heightened by research and extension programs in some States. However, awareness is by no means universal. Soil acidification is a cost of productive agricultural systems—whether from nitrogen fixation by legumes in mixed pastures or crop rotations, or from the increased use of nitrogen fertilisers.

In the absence of remedial lime applications, (which neutralise acidity) it was estimated that from 29 to 60 million hectares will reach the limiting soil pH value of 4.8 within 10 years, and a further 14 to 39 million hectares will reach the pH value of 5.5, where growth of sensitive plant species is impaired.

Currently, approximately 2 million tonnes of lime are applied to agricultural land each year and use is generally increasing. It has been estimated that from 12 to 66 million tonnes of lime is required to adjust Australia's existing acidic soils to pH values of 4.8 and 5.5 respectively, with a further 3 to 12 million tonnes needed each year to maintain soil pH status in a satisfactory range. These estimates indicate the imperatives for coordinated extension activities across industry groups, agribusiness and government.

Land degradation problems arising from induced acidification are mostly reversible by applying lime. Other management solutions can be used where liming is not a viable option. In northern Queensland banana plantations, improvements in nitrogen and residue management reduced the need for lime.

Other opportunities include stock management and attention to the use of perennials in the pasture management cycle.

Erosion

Water-borne soil erosion is a major and continuing issue for Australian agriculture and catchment management and impacts on river, estuary and marine resources. It causes unsustainable losses of soil for agriculture that in some areas far exceed (up to 50 times) rates of soil development.

Hillslope erosion (sheet and rill erosion) remains high in Australia's tropical northern regions, particularly at the onset of the wet season, and especially in the semi-arid woodlands and arid interior. Maintaining vegetative cover, minimising soil disturbance and building sediment-trapping wetlands and riparian areas remain imperatives.

Gully erosion while inactive in many previously formed gullies, persists as the major erosion process affecting river condition in southern and eastern Australia. Sediment from these previously active gullies has affected about 10 000 kilometres of stream length in the Murray–Darling Basin alone. These rivers, now with coarse sand accumulations in stream beds, exacerbating flooding and smothering habitat of Australia's native fish.

Active gully erosion is still occurring in northern Queensland and in south-western regions of Western Australia. Changes to agricultural practices that minimise gully erosion is an imperative, from both on- and off-farm perspectives.

River bank erosion is a major problem. Extensive lengths (120 000 kilometres) of riparian vegetation along eastern Australia's rivers and streams are degraded and require rehabilitation. Where these landscape resources are intact, they protect the integrity of banks against erosion. Priority areas include much of the Murray–Darling Basin, South Australia and south-western regions of Western Australia.

Sediment delivery to streams, rivers, estuaries and near shore marine zones is high in many catchments. Deposition of sand and suspended sediments in streams and rivers is worst in the Murray–Darling Basin, coastal regions of New South Wales, south-east Queensland and the south west of Victoria.

From a near shore marine and estuary perspective, approximately 90% of suspended sediment loads reaching marine and estuarine environments is derived from 20% of agricultural catchments particularly in coastal regions of Queensland and New South Wales.

For the Great Barrier Reef Lagoon, about 25% or 12 million tonnes of sediment delivered to streams is discharged each year on average across all contributing catchments. This is predicted to be approximately three times greater than natural loads, with consequent impacts on estuaries and marine fisheries, seagrasses and near shore coral reefs. However for catchments such as the Burdekin and Fitzroy, loads can be more than 20 times natural loads

National, State and regional priorities for natural resources management can now be re-appraised in the light of these findings (e.g. soil loss on farm is irreversible and impacts that occur off-farm which will continue for many generations). Catchment management and industry priorities, particularly in terms of implementing improved practice are essential. Total impacts are likely to be equal to, if not greater than, those of dryland salinity. It is imperative that soil management targets hillslope, gully and river bank erosion in the areas identified by this assessment.

Nutrient loads to Australian rivers and estuaries

Nearly 19 000 tonnes of total phosphorus and 141 000 tonnes of total nitrogen are exported to Australia's coast each year from areas of intensive agriculture: highest exports are in northern Queensland, Moreton Bay and New South Wales.

Total nutrient loads from river basins are partly dictated by sediment load and therefore basin size—the bigger the basin, the bigger the load. Smaller basins can export large loads if they have high export rates due to high slopes and intense rainfall; increases in population, or changes in land use and management.

Efficiency of phosphorus delivery from Australia's rivers to the coast varies from as low as 3% in the Murray–Darling Basin to over 90% in Tasmania.

The major sink for phosphorus is floodplain sedimentation, but reservoir sedimentation (both nitrogen and phosphorus) and riverine denitrification (nitrogen only) can account for substantial proportions.

Priorities for reducing river and estuarine nutrient loads vary—large relative increases in river nutrient loads do not always coincide with large total exports, and estuaries differ in their sensitivity to increases in nutrient loading particularly because of differences in residence times and tidal flushing.

Targeted erosion control and soil management provides a significant contribution to managing the supply of nutrients with much of the nutrient accompanying increased sediment loads to most rivers.

Where a large part of the increase is caused by increases in either surface run-off loads or point source discharges, close attention needs to be paid to fertiliser application, animal waste retention on-farm, and sewage treatment plant and septic tank effluent management.

Agricultural practice

Australian agricultural industries have continuously implemented new or innovative practices. In more recent years, farmers have adopted:

- improved crop rotations;
- reduced tillage and stubble retention/ incorporation by the grains industry (to reduce wind and water soil erosion and improve soil health);
- green trash blanketing by the sugar industry (to add flexibility to harvest and reduce soil erosion); and
- potassium fertiliser and lime use in agricultural systems of Western Australia (identified as significant nutritional limitations).

The Audit assessment of farming practices across all agricultural industries has demonstrated how 'best management practice' is an evolving part of agriculture. Industry has a commitment to development and adoption of best management practice. A key agent for change will be linking practices and environmental stewardship to improvements in farm business profitability.

Ways forward

Australian agriculture has shown its capacity to adapt and innovate in response to environmental challenges. Australian farmers are conscious of the need to manage their natural resources sustainably, delivering a 'clean and green' product and working hard to manage their activities within the broader context of catchment management. Continuous improvement in practice is the framework to deliver sustainable outcomes.

Australia could enhance its capacity to deliver both productivity outcomes on-farm and environmental benefits off-farm with:

- continued definition and improvement of best practice and tracking of implementation;
- leadership in monitoring and reporting from industries and their research and development corporations;
- soil management including soil erosion control and revegetation of riparian lands; and
- increased attention to soil fertility, pH and nutrient balance.

All these issues are best addressed through partnerships between industry groups, agribusiness, research and development corporations and government. Australian Agriculture Assessment 2001 has provided the information basis to improve natural resource management by Australian agriculture.

It remains for Australian agriculture and its support groups to keep this information current as a basis for tracking progress and setting priorities.

Australian Natural Resources Atlas

Access to information on natural resources provides opportunities for increased awareness and informed debate. This access has been improved through internet and database technology. The interactive web-based Australian Natural Resources Atlas (Atlas) presents Audit products at scales from local to regional to national.

The Atlas provides information to aid decision making across all aspects of natural resource management. It covers the broad topic of water, land, agriculture, people and ecosystems. The Atlas presents information by geographic region (national, State, regional) and by information topic. Users of the Atlas can prepare a map—using the 'make a map facility'—or search hundreds of reports in a matter of seconds.

The Australian Natural Resources Data Library supports the Atlas with links to Commonwealth, State and Territory data management systems.

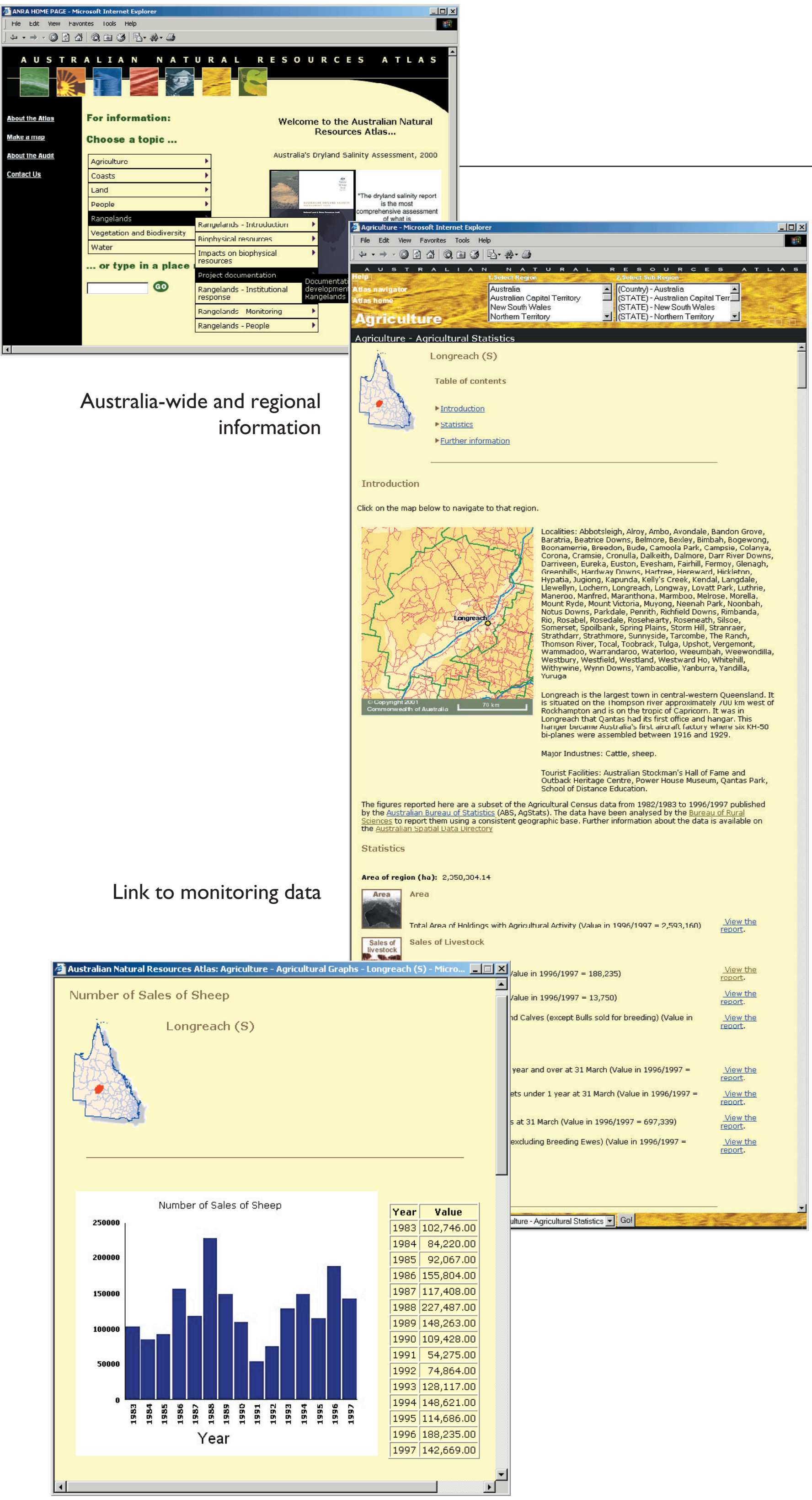
The outputs of Australian Agriculture Assessment 2001 have been reported in the *Agriculture* and *Land* topics of the Atlas.

Audit reports

NLWRA 2001a, *Australian Dryland Salinity Assessment 2000*, a theme report for the National Land and Water Resources Audit, Canberra.

NLWRA 2001b, *Australian Water Resources Assessment 2000*, a theme report for the National Land and Water Resources Audit, Canberra.

NLWRA 2001c, *Tracking Changes. Australian Collaborative Rangeland Information System*, a theme report for the National Land and Water Resources Audit, Canberra.



Welcome to the Australian Natural Resources Atlas...

Australia's Dryland Salinity Assessment, 2000

"The dryland salinity report is the most comprehensive assessment of what is

Agriculture - Agricultural Statistics

Longreach (S)

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Introduction

Click on the map below to navigate to that region.

Localities: Abbotsleigh, Alroy, Ambo, Avondale, Bandon Grove, Baratria, Beatrice Downs, Belmore, Bexley, Bimbah, Bogewong, Boonamerrie, Breedon, Bude, Camoola Park, Campsie, Colanya, Corona, Cramsie, Cronulla, Dalkeith, Dalmore, Darr River Downs, Darriveen, Eureka, Euston, Evesham, Fairhill, Fermoy, Glenagh, Greenhills, Hardway Downs, Hartree, Hereward, Hickleton, Hypatia, Jugiong, Kapunda, Kelly's Creek, Kendal, Langdale, Llewellyn, Lochern, Longreach, Longway, Lovatt Park, Luthrie, Maneroo, Manfred, Maranthona, Marmboo, Melrose, Morella, Mount Ryde, Mount Victoria, Muyong, Neenah Park, Noonbah, Notus Downs, Parkdale, Penrith, Richfield Downs, Rimbanda, Rio, Rosabel, Rosedale, Rosehearty, Roseneath, Silsoe, Somerset, Spoilbank, Spring Plains, Storm Hill, Stranraer, Strathdarr, Strathmore, Sunnyside, Tarcombe, The Ranch, Thomson River, Tocal, Toobrack, Tulga, Upshot, Vergemont, Wammadoo, Warrandaroo, Waterloo, Weeumbah, Weewondilla, Westbury, Westfield, Westland, Westward Ho, Whitehill, Withywine, Wynn Downs, Yambacollie, Yanburra, Yandilla, Yuruga

Longreach is the largest town in central-western Queensland. It is situated on the Thompson river approximately 700 km west of Rockhampton and is on the tropic of Capricorn. It was in Longreach that Qantas had its first office and hangar. This hanger became Australia's first aircraft factory where six KH-50 bi-planes were assembled between 1916 and 1929.

Major Industries: Cattle, sheep.

Tourist Facilities: Australian Stockman's Hall of Fame and Outback Heritage Centre, Power House Museum, Qantas Park, School of Distance Education.

The figures reported here are a subset of the Agricultural Census data from 1982/1983 to 1996/1997 published by the Australian Bureau of Statistics (ABS, AgStats). The data have been analysed by the Bureau of Rural Sciences to report them using a consistent geographic base. Further information about the data is available on the Australian Spatial Data Directory

Statistics

Area of region (ha): 2,350,304.14

Area

Total Area of Holdings with Agricultural Activity (Value in 1996/1997 = 2,593,160) View the report.

Sales of Livestock

/alue in 1996/1997 = 188,235) View the report.

/alue in 1996/1997 = 13,750) View the report.

nd Calves (except Bulls sold for breeding) (Value in View the report.

year and over at 31 March (Value in 1996/1997 = View the report.

ets under 1 year at 31 March (Value in 1996/1997 = View the report.

s at 31 March (Value in 1996/1997 = 697,339) View the report.

excluding Breeding Ewes) (Value in 1996/1997 = View the report.

Number of Sales of Sheep

Longreach (S)

Year	Value
1983	102,746.00
1984	84,220.00
1985	92,067.00
1986	155,804.00
1987	117,408.00
1988	227,487.00
1989	148,263.00
1990	109,428.00
1991	54,275.00
1992	74,864.00
1993	128,117.00
1994	148,621.00
1995	114,686.00
1996	188,235.00
1997	142,669.00

Australia-wide and regional information

Link to monitoring data

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Australian Soil Resources Information System—detailed description

Volume 2

AUSTRALIAN AGRICULTURE ASSESSMENT 2001: IN CONTEXT

Landscapes processes and productivity

Australian Agriculture Assessment 2001 reports on landscape processes, soil, nutrient and water movement and serves as a key input towards improved land and water resources management.

Australian Agriculture Assessment 2001:

- shows how and to what extent agriculture has **changed water and nutrient balances**;
- assesses **nutrient inputs and outputs from agriculture** and the implications for nutrient management on-farm;
- forecasts the impact of **soil acidification** on agricultural soils and productivity;
- presents the first comprehensive assessment of **water-borne erosion** and **sediment transport** for Australia's agricultural catchments and rivers and highlights implications for soil, river and estuary management;
- presents **river nutrient budgets** and changes for nitrogen and phosphorus;
- describes characteristics of **Australia's soils** that influence production, and soil and landscape processes;
- highlights the **progress of agricultural industries** in meeting natural resource challenges; and
- identifies key components of **land condition monitoring** so that natural resource changes and outcomes can be measured in the future.

Australian Agriculture Assessment 2001 has drawn on a number of other Audit activities. This report should be read in conjunction with these assessments.

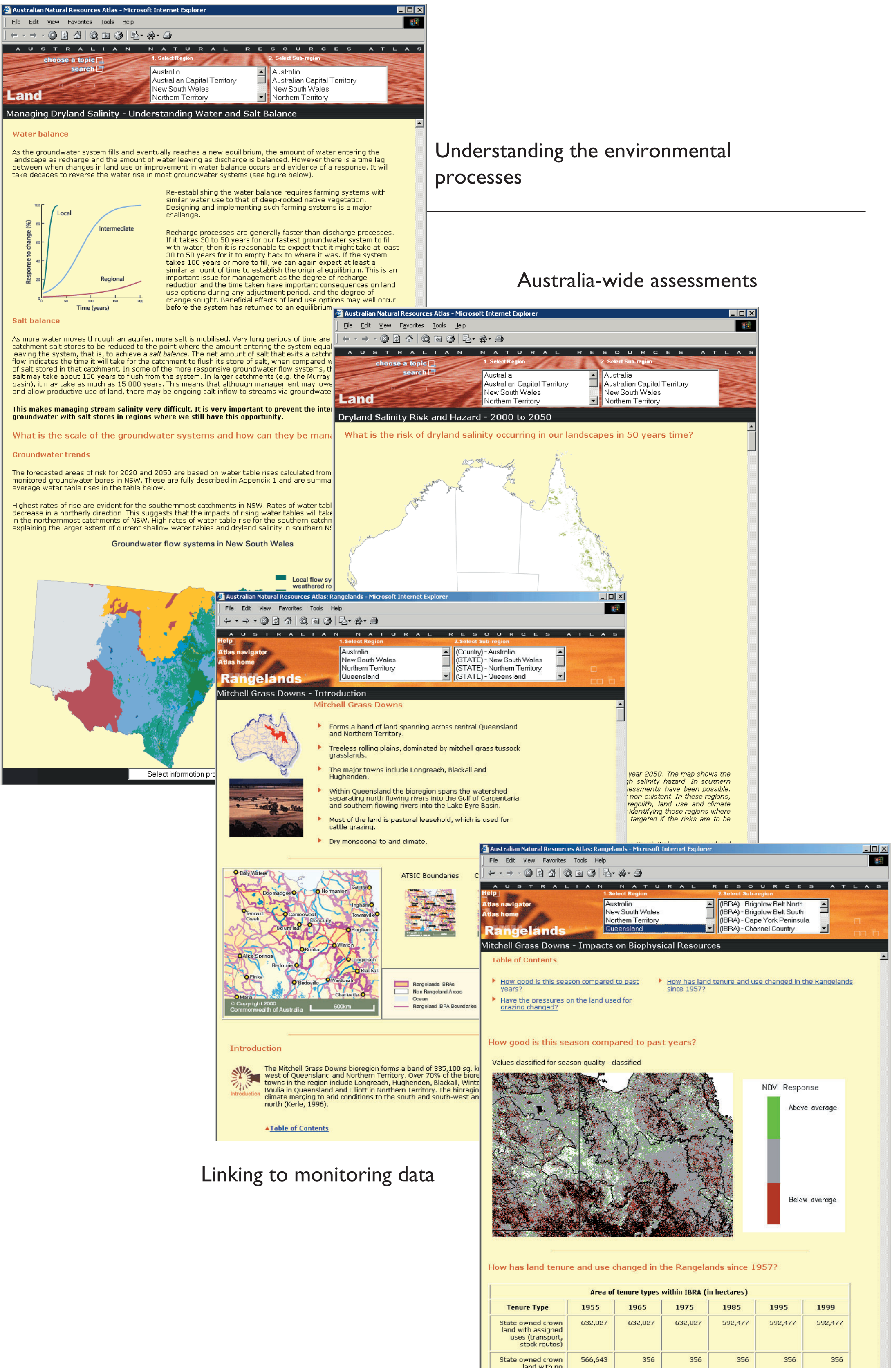
Dryland salinity. Assessment of the extent of, and management options for, dryland salinity are presented in *Australian Dryland Salinity Assessment 2000*. To address dryland salinity, for example, Australia needs to make major changes in water balance in many catchments. This will require changes in agricultural land use patterns and land management activities so that targets for protection of downstream land and water resources are met. *Australian Agriculture Assessment 2001* details related natural resource issues that must also be taken into account.

Economic returns and costs of resource use. Major opportunities to increase economic activity, and at the same time enhance environmental and social benefits are generated by water resources through water resource development and improved water use efficiency. Assessment of economic returns of agriculture and impacts and costs of resource change will be presented as part of the *Australians and natural resource management 2001* report. *Australians and natural resource management 2001* builds on *Australian Agriculture Assessment 2001* and *Australian Dryland Salinity Assessment 2000* to provide the social and economic context for the next phase of natural resource management in Australia.

Vegetation and biodiversity. Integrating native vegetation and biodiversity management objectives with agricultural development and practice is clearly an important issue for the future of Australian agriculture. The Audit's *Landscape health in Australia*, *Australian Native Vegetation Assessment 2001* and *Australian Biodiversity Assessment* (due for release in 2002) provide important baseline information on the extent, threats and condition of Australia's natural assets. This information will help government and industry to set priorities for activities to achieve ecologically sustainable development.

Catchment, river and estuary impacts. While sediment and nutrient loads are reported as part of Australian Agriculture Assessment 2001, the ecological impact of the changes to hydrology, habitat, sediment and nutrient regimes will be presented as part of the *Australian Catchment, Rivers, Estuary Assessment 2001* report.

Access to data and information. Government and public alike seek improved and more accessible information on our natural resources. Access to information increases opportunities for informed debate. Audit activities have improved access to natural resources information through internet and database technology. The National Land and Water Audit's Australian Natural Resources Atlas and Data Library—www.nlwra.gov.au/atlas—provides access to summary data and information at national, State and regional scales as well as an access point to project documentation underpinning this summary report.



Understanding the environmental processes

Managing Dryland Salinity - Understanding Water and Salt Balance

Water balance

As the groundwater system fills and eventually reaches a new equilibrium, the amount of water entering the landscape as recharge and the amount of water leaving as discharge is balanced. However there is a time lag between when changes in land use or improvement in water balance occurs and evidence of a response. It will take decades to reverse the water rise in most groundwater systems (see figure below).

Re-establishing the water balance requires farming systems with similar water use to that of deep-rooted native vegetation. Designing and implementing such farming systems is a major challenge.

Recharge processes are generally faster than discharge processes. If it takes 30 to 50 years for our fastest groundwater system to fill with water, then it is reasonable to expect that it might take at least 30 to 50 years for it to empty back to where it was. If the system takes 100 years or more to fill, we can again expect at least a similar amount of time to establish the original equilibrium. This is an important issue for management as the degree of recharge reduction and the time taken have important consequences on land use options during any adjustment period, and the degree of change sought. Beneficial effects of land use options may well occur before the system has returned to an equilibrium

Salt balance

As more water moves through an aquifer, more salt is mobilised. Very long periods of time are
catchment salt stores to be reduced to the point where the amount entering the system equal
leaving the system, that is, to achieve a *salt balance*. The net amount of salt that exits a catchm
flow indicates the time it will take for the catchment to flush its store of salt, when compared w
of salt stored in that catchment. In some of the more responsive groundwater flow systems, th
salt may take about 150 years to flush from the system. In larger catchments (e.g. the Murray
basin), it may take as much as 15 000 years. This means that although management may lowe
and allow productive use of land, there may be ongoing salt inflow to streams via groundwate

This makes managing stream salinity very difficult. It is very important to prevent the inter
groundwater with salt stores in regions where we still have this opportunity.

What is the scale of the groundwater systems and how can they be mana

Groundwater trends

The forecasted areas of risk for 2020 and 2050 are based on water table rises calculated from
monitored groundwater bores in NSW. These are fully described in Appendix 1 and are summa
average water table rises in the table below.

Highest rates of rise are evident for the southernmost catchments in NSW. Rates of water tabl
decrease in a northerly direction. This suggests that the impacts of rising water tables will take
in the northernmost catchments of NSW. High rates of water table rise for the southern catchm
explaining the larger extent of current shallow water tables and dryland salinity in southern N

Groundwater flow systems in New South Wales

Australia-wide assessments

Dryland Salinity Risk and Hazard - 2000 to 2050

What is the risk of dryland salinity occurring in our landscapes in 50 years time?

year 2050. The map shows the
gh salinity hazard. In southern
sessments have been possible.
non-existent. In these regions,
regolith, land use and climate
identifying those regions where
targeted if the risks are to be

Mitchell Grass Downs - Introduction

Mitchell Grass Downs

- Forms a band of land spanning across central Queensland and Northern Territory.
- Treeless rolling plains, dominated by mitchell grass tussock grasslands.
- The major towns include Longreach, Blackall and Hughenden.
- Within Queensland the bioregion spans the watershed separating north flowing rivers into the Gulf of Carpentaria and southern flowing rivers into the Lake Eyre Basin.
- Most of the land is pastoral leasehold, which is used for cattle grazing.
- Dry monsoonal to arid climate.

Introduction

The Mitchell Grass Downs bioregion forms a band of 335,100 sq. k
west of Queensland and Northern Territory. Over 70% of the biore
towns in the region include Longreach, Hughenden, Blackall, Wint
Boulia in Queensland and Elliott in Northern Territory. The bioregio
climate merging to arid conditions to the south and south-west an
north (Kerle, 1996).

▲Table of Contents

Mitchell Grass Downs - Impacts on Biophysical Resources

Table of Contents

- How good is this season compared to past years?
- Have the pressures on the land used for grazing changed?
- How has land tenure and use changed in the Rangelands since 1957?

How good is this season compared to past years?

Values classified for season quality - classified

How has land tenure and use changed in the Rangelands since 1957?

Area of tenure types within IBRA (in hectares)

Tenure Type	1955	1965	1975	1985	1995	1999
State owned crown land with assigned uses (transport, stock routes)	632,027	632,027	632,027	592,477	592,477	592,477
State owned crown land with no	566,643	356	356	356	356	356

Linking to monitoring data

Australian Natural Resources Atlas: www.nlwra.gov.au/atlas

IN PARTNERSHIP

Cooperation and commitment

Australian Agriculture Assessment 2001 was prepared in partnership with:

- CSIRO Land and Water
- Agriculture, Fisheries, Forestry – Australia: Bureau of Rural Sciences; Australian Bureau of Agricultural and Resource Economics
- Department of Land and Water Conservation, New South Wales
- New South Wales Agriculture
- Department of Lands, Planning and Environment, Northern Territory
- Department of Natural Resources and Environment, Victoria
- Department of Natural Resources and Mines, Queensland
- Department of Primary Industries, Water and Environment, Tasmania
- Primary Industries and Resources South Australia
- Agriculture Western Australia
- Fertilizer Industry Federation of Australia
- Dairy Research and Development Corporation & Australian Dairy Farmers Federation
- Horticulture Australia Ltd (formerly Horticulture Research and Development Corporation)
- Murray-Darling Basin Commission
- Numerous industry groups, and research and development corporations who contributed data, information and case studies.

A list of contributing projects is provided in the acknowledgments at the end of this report.

AUSTRALIAN AGRICULTURE: SETTING THE SCENE

SUMMARY

- Climate, soil quality, topography and the availability of irrigation water determine agricultural land use patterns and production potential in Australia.
- Development of agriculture has had to confront and overcome constraints imposed by an unreliable and generally semi-arid climate, and often fragile and infertile soils.
- Irrigated agriculture has expanded markedly in recent decades to over 2 million hectares. It now contributes about a quarter of the total gross value of national agricultural production.
- Agricultural land use systems and farming practices have progressively evolved. They continue to move towards being more efficient in resource use and becoming sustainable. These goals have yet to be universally or fully realised.
- Agricultural development has disturbed the rate and sometimes the direction of the ecological processes of natural landscapes. Some types of degradation (e.g. soil loss by erosion and dryland salinity) have long-term or irreversible consequences; other forms (e.g. leaching of nutrients, surface acidification) can be remedied with appropriate actions.
- Many Australian soils do not naturally have the qualities needed for sustained agricultural production without significant management inputs.

Economic and social dimensions of natural resource management

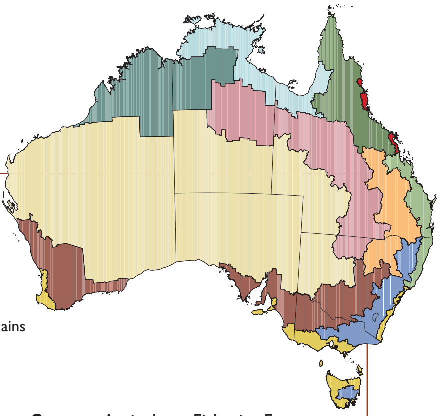
- *Australian Agriculture Assessment 2001* reports on landscape processes, soil, nutrient and water movement and serves as a key input to the Audit report on the social and economic dimensions of natural resource management—*Australians and Natural Resource Management 2001*.

AUSTRALIAN AGRICULTURAL INDUSTRIES

Australia's modern agricultural industries have grown by progressively expanding in area, diversity and volume of production. Research, trial and error, and innovation have overcome the challenges posed by an unpredictable and variable climate, mainly infertile soils and large distance to markets. Much was learned and is still being learned as land use systems and farming practices continue to evolve and adjust to the Australian environment.

Today, Australia's agricultural landscapes are diverse, defined by interrelationships between landscape resources (especially hydrology, soil quality and topography), climatic constraints and the availability of irrigation water. Eleven broad agro-ecological regions (Figure 1.1) are recognised (SCARM 1998) and help the description of the dominant systems of land use (Figure 1.2).

Figure 1.1 Agro-ecological regions of Australia.

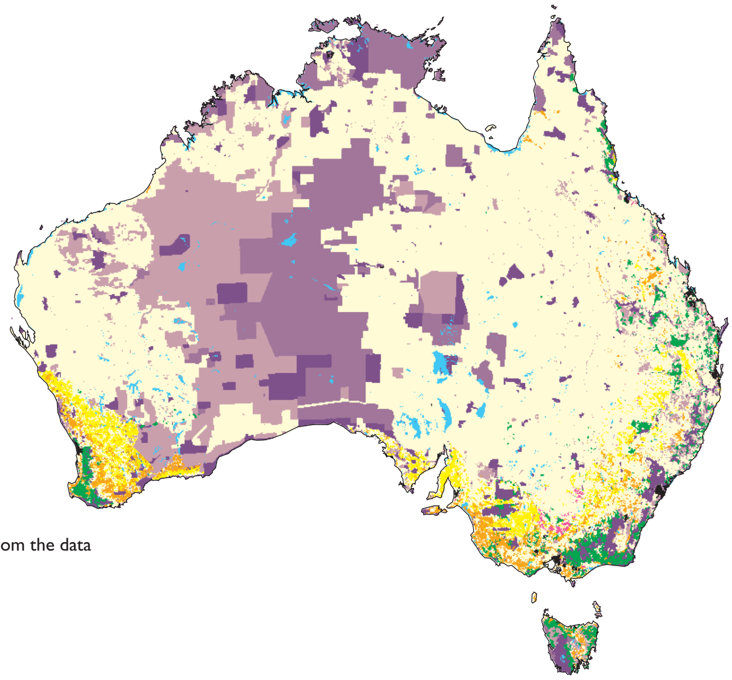


Source: Agriculture Fisheries Forestry – Australia 1996.

Agro-ecological regions (AER)

- Vast areas of sparsely stocked, arid and semi-arid rangelands, that include conservation and aboriginal land areas (AER 1, 2, 3, 5, 11).
- Mixed farming regions, where livestock and crop production systems (or 'ley' or 'phase' farming) co-exist. These are mostly under dryland conditions—sometimes referred to as the 'wheat–sheep' zone—(AER 10) and the subtropical cropping–livestock zone (AER 6).
- Higher rainfall, permanently grazed pastures, sometimes interspersed with horticultural enterprises in the winter-dominant rainfall zones of southern Australia (AER 8 and 9).
- Sugar cane and horticultural production located on the wet tropical (AER 4) subtropical coastal regions (AER 7).
- Highly intensive pig and poultry industries and cattle feedlot systems, with the latter being located mainly on the coastal hinterland of Queensland and New South Wales, but occupying only small areas of land.
- Intensive horticulture and livestock are commonly located close to the capital cities.

Figure 1.2 National land use map.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

During the past 45 years, the area of irrigated land (Figure 1.3) has quadrupled to over 2 million hectares, (or 1% of the total agricultural land). It produces 26% of the gross value of production from Australia's agriculture. Increases in irrigation have occurred in pastures used for dairying, cereal crops, cotton, sugar cane, fruit and vegetables.

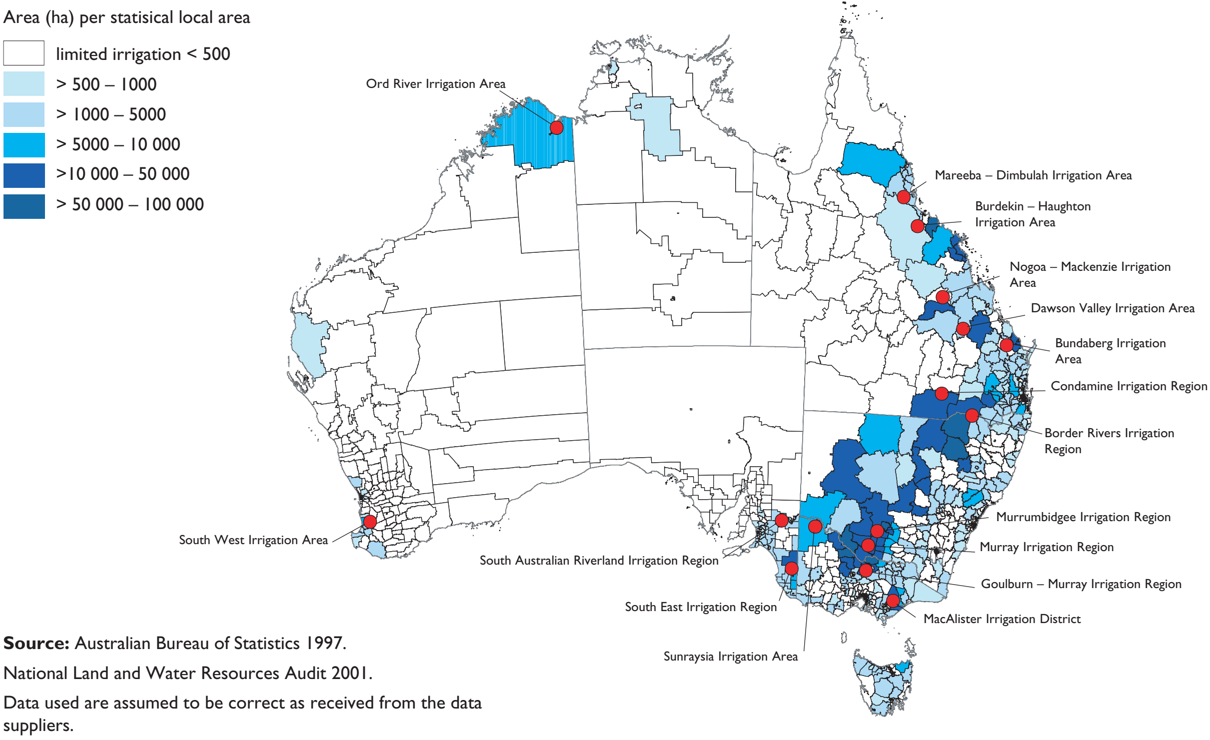
Significant differences in agriculture occur when irrigation is possible. The efficient use of the applied water is of paramount importance for these intense forms of agricultural land uses.

A diverse range of agricultural products is produced for national consumption. Industries also earn valuable export income by supplying a significant proportion of world trade in wool, meats, grains and more recently in wine (see *Profile of Australian Agriculture* section).

Industry development is supported by transport (roads, rail and ports) and irrigation infrastructures, an agricultural service sector, and a research and extension capability. Value-adding secondary industries turn raw agricultural produce into food and fibre products.

Australian Agriculture Assessment 2001 has concentrated mainly within the 'intensive agriculture' regions, (as distinct from agriculture practised in the semi-arid rangelands). A key output is aggregated material budget data on the impacts of agriculture on river nutrient budgets and soil erosion presented at river basin scales (Appendix 1).

Figure 1.3 Irrigated areas of Australia (1997).



Source: Australian Bureau of Statistics 1997.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

AGRICULTURE IN AUSTRALIA'S NORTHERN 'TOP END' REGIONS

The so-called 'Top End' of Australia is defined as the tropical northern third of the Northern Territory and the Ord River Irrigation Area of north-west Western Australia (see Figure 1.2). Relative to other agricultural regions in Australia's intensive land use zone, the actual area used, the size of individual agricultural industries and supporting population are small. However, potential increase in agricultural production is considered high, provided systems suitable for the social and environmental conditions of this region can be developed (e.g. approximately 13 000 hectares of land is currently irrigated from the Ord River Stage 1, with an additional 43 000 hectares proposed for development under Stage 2).

Agricultural industries being pioneered and developed in these regions face many social, economic and environmental challenges, including relatively high freight costs. As a result, high value, niche market crops are produced to maximise returns and ensure market penetration within Australia or overseas.

Both successes and failures have occurred in the region, (as there have been elsewhere), but over the past two decades the agricultural base has slowly expanded and diversified. It continues to be an important component of the regional economy. There is a large capacity to further expand both dryland and irrigated agriculture in this region (see below), while ensuring current development and management practice supports concepts of sustainability.

The Top End also enjoys some distinct market advantages, because of its proximity to South East Asia and its ability to supply a diverse range of quality, early and out-of-season produce to southern Australian States and northern hemisphere markets.

The beef cattle industry

Cattle grazing is the dominant agricultural industry across this vast region of Australia. In 2000, the gross value of cattle produced ($189 million and a total of 449 000 head) from Northern Territory pastoral properties (including southern regions). This comprised 64% of the total gross value of the Territory's agricultural sector economy. A major proportion of cattle turned off were exported live overseas: 27% of Australia's total live cattle trade and 40% of sales to South East Asia are now exported through Port Darwin (240 000 head in 2000). Substantial cattle numbers were also shipped interstate.

The export beef industry in the Territory is also supported by an irrigated hay industry located at Katherine, Douglas/Daly and Darwin. Forage sorghum, maize and leucaena (a forage legume shrub) are also grown on the Ord to finish off rangeland cattle.

Horticultural industries

A diverse range of horticultural fruit and vegetable crops is produced under irrigation in the Ord River Valley ($31 million in 1998) and the Northern Territory ($88 million in 2000) and is destined to reach domestic markets in southern Australia and some overseas destinations. Melons and pumpkins alone comprised 40% of the total agricultural productivity generated in the Ord Valley in 1998 (Anon 1999). Horticultural crops, including mangoes, table grapes, bananas and vegetables constitute about 30% of the gross value of agricultural production from the Northern Territory, with 80% being shipped to Australian States.

It is projected that irrigated horticultural enterprises will continue to expand in the Top End as suitable land and water resources are released.

Other industries

In the Ord River Irrigation Area, sugar cane has emerged as a significant crop. Insect-resistant cotton is also being re-examined. Hybrid seed crops of sorghum, sunflower, maize and millet are also established industries in the Ord Valley.

New irrigation prospects

The development of Stage 2 of the Ord River Project could eventually bring expanded areas of irrigated field crops (e.g. sugar cane) and smaller areas for intensive horticulture (e.g. bananas, mangoes and tropical fruits and vegetables) into production. Approximately half of this cropping expansion, utilising water from the Ord River, will be located in the Northern Territory. Expansion in these commodities will also occur in the other parts of the Northern Territory as land becomes available.

In the Northern Territory, government resource planners estimate that the area of irrigated agriculture could sustainably expand 30 to 40 times greater than its present level. Based on an annual water consumption of 10 megalitres per hectare, the area for potential irrigation in the Top End was projected to be 85 600 and 27 500 hectares respectively for surface and ground water reserves. This assessment (Table 1.1) required no in-stream dams to be constructed, ensured adequate water allocations were available for environmental river flows (80% of stream flow and/or recharge) and required land clearances in river basins of less than 4%.

Table 1.1 Projected area with potential for irrigation development in the Top End region.

- Top End irrigation potential (at 10 ML/ha/yr)
- Groundwater irrigated area 27 500 ha
- Surface water irrigated area 85 600 ha
- Off-stream dams 25 700 ha
- Lake Argyle dam 125 000 ha

River basin	**Basin area**	**Annual irrigation** (10ML/ha/yr)	**Total basin clearing** (irrigation, fallow, dams)	
	(km^2)	(ha/year)	(ha)	% of Basin
Ord River	55 380			
Groundwater		nil	nil	nil
Surface water		56 000	181 000	3.3
Victoria River	77 230			
Groundwater		nil	nil	
Surface water		10 400	34 300	0.5
Moyle River	7 020			
Groundwater		5 000	15 000	2.2
Surface water		nil	nil	nil
Adelaide River	7 430			
Groundwater		nil	nil	nil
Surface water		4 000	13 200	1.8
Mary River	8 060			
Groundwater		2 500	7 500	1.0
Surface water		nil	nil	nil
Blyth River	9 080			
Groundwater		2 500	7 500	0.9
Surface water		nil	nil	nil
Roper River	79 130			
Groundwater		3 000	9 000	0.1
Surface water		14 400	47 500	0.6
Daly River	52 940			
Groundwater		14 500	43 500	0.8
Surface water		40 000	132 000	2.5
McArthur River	19 200			
Groundwater		nil	nil	nil
Surface water	19 220	16 800	55 400	2.9

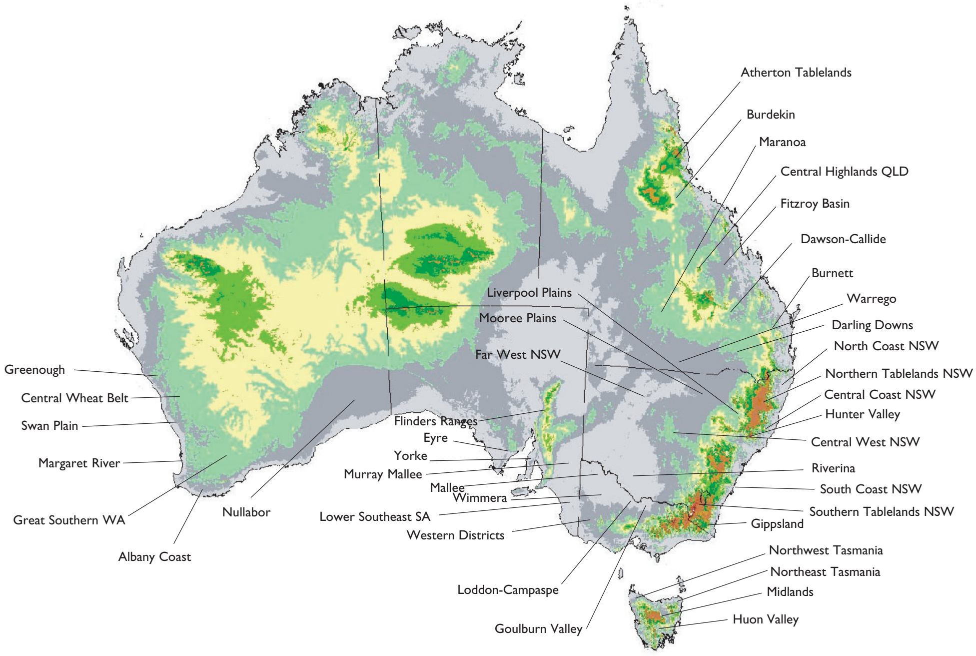
Source: Northern Territory Department of Lands, Planning and Environment

Landscape

Australia's 760 million hectares possess some unique and diverse features when compared with other continents:

The continent is broad and flat with few hills and basins. Its low average elevation and relief (rarely greater than 1600 metres and the lowest of any continent) is partly due to the absence of volcanic and tectonic activity in recent geological time and to prolonged wind and water erosion. The Great Dividing Range, located inland from the eastern seaboard provides the main upland topographic relief and alpine areas (Figure 1.4).

Figure 1.4 Topographic map of Australia listing major agricultural areas (grey is lowest and red is highest elevation).



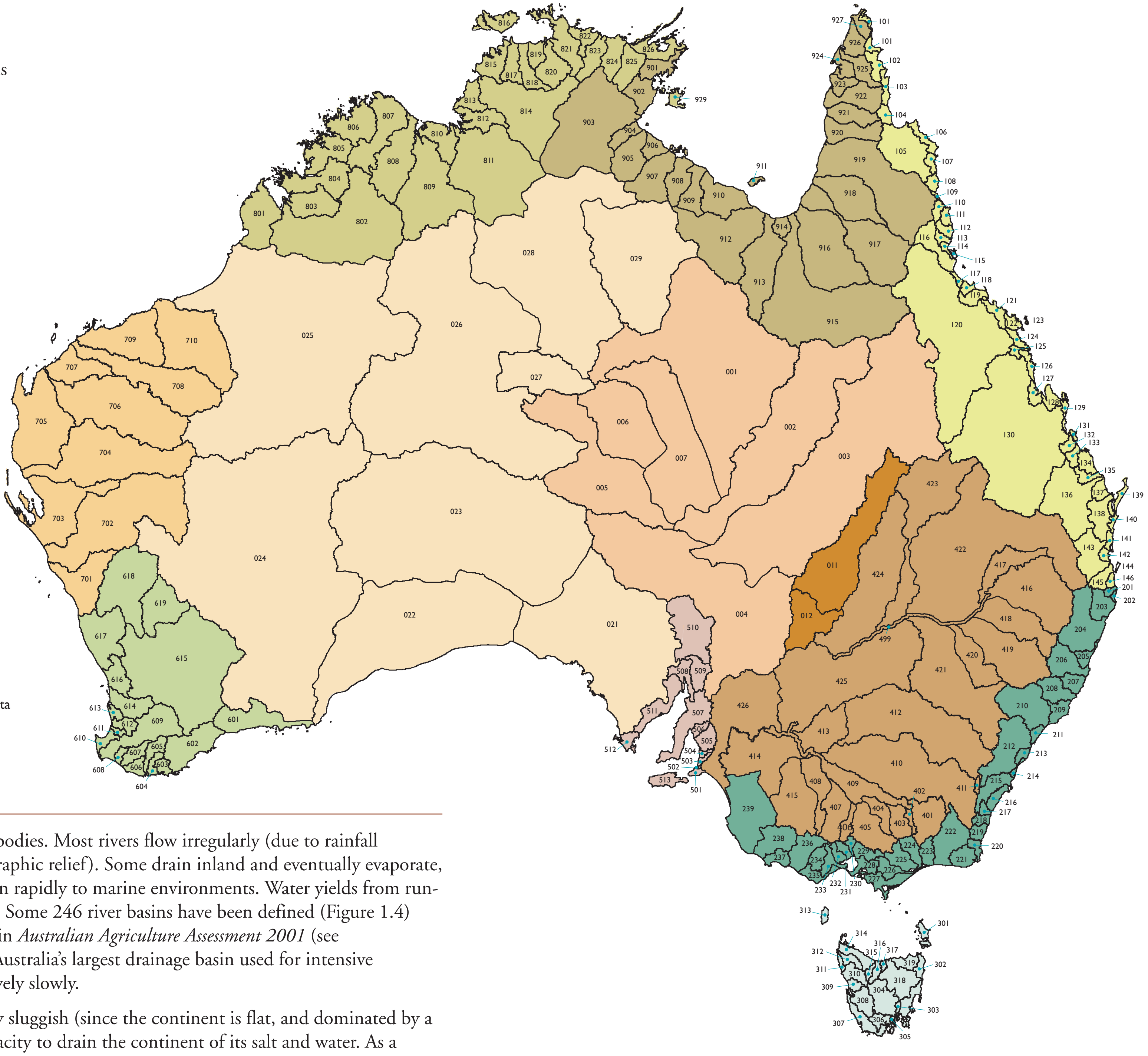
Source: AUSLIG.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 1.5 Australia's river basins.

Further information on Australia's river basins is contained in Appendix 1.



Source: AUSLIG 1997.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Australia has few major rivers or fresh water bodies. Most rivers flow irregularly (due to rainfall variability) and slowly (because of low topographic relief). Some drain inland and eventually evaporate, while coastal rivers in steeper terrain can drain rapidly to marine environments. Water yields from run-off are usually very low (except in Tasmania). Some 246 river basins have been defined (Figure 1.4) and used as the basis for aggregate reporting in *Australian Agriculture Assessment 2001* (see Appendix 1). The Murray–Darling Basin is Australia's largest drainage basin used for intensive agriculture. Its contributing rivers flow relatively slowly.

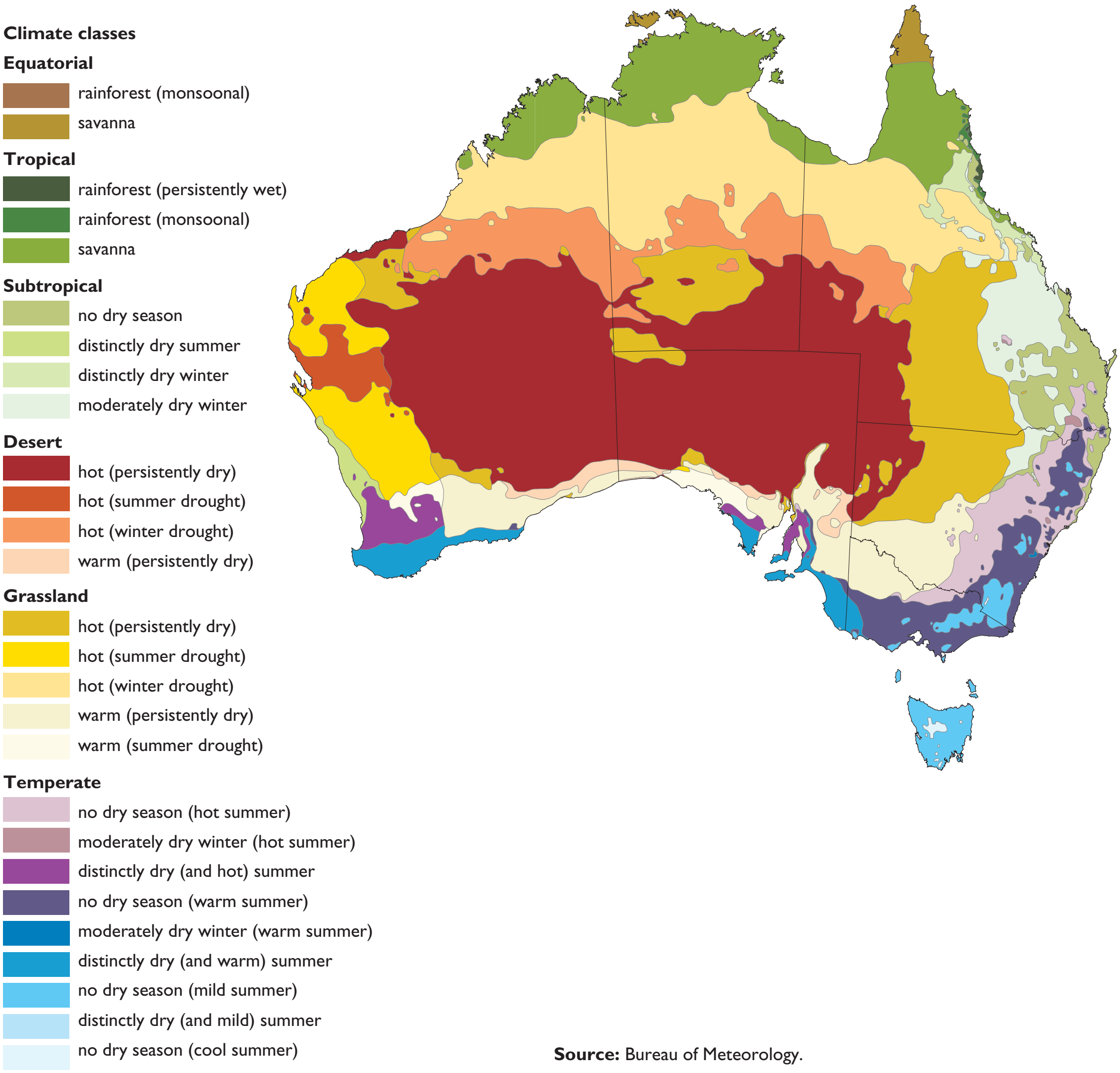
Most rivers and groundwater systems are very sluggish (since the continent is flat, and dominated by a gentle fall towards its interior) with little capacity to drain the continent of its salt and water. As a consequence, enormous stores of salt characterise Australian landscapes.

Australia's variable climate

Rainfall

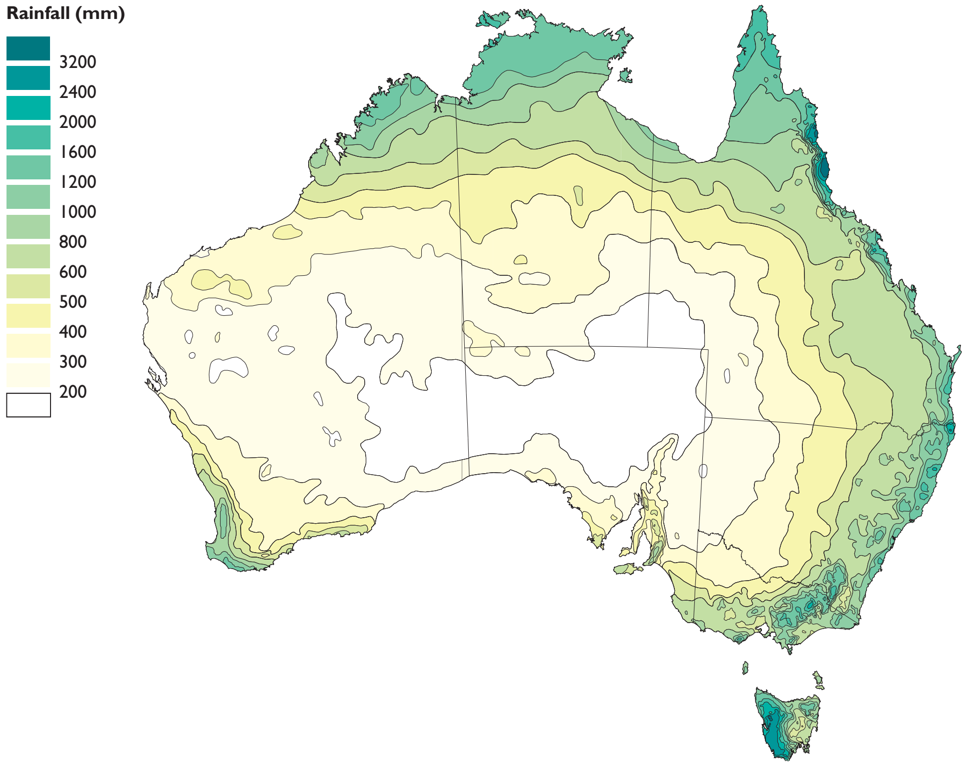
Australia is the driest inhabited continent in the world. It has extreme variations in climatic conditions (Figures 1.6, 1.7) covering tropical, subtropical, desert, temperate, Mediterranean and subalpine climates (Figure 1.8).

Figure 1.6 Australia's climate types (Koppen classification).



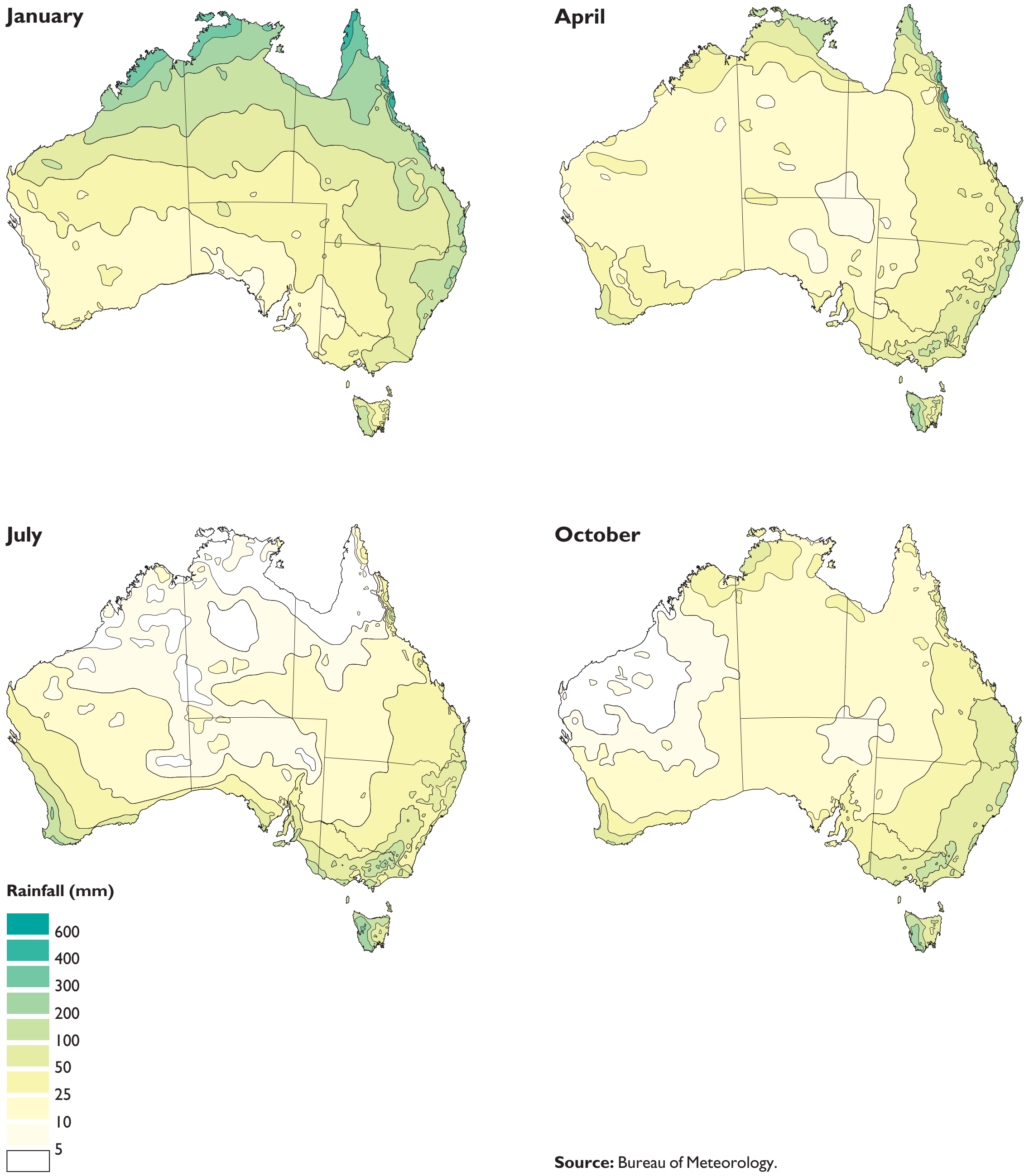
Source: Bureau of Meteorology.

Figure 1.7 Mean annual rainfall for Australia.



Source: Bureau of Meteorology.

Figure 1.8 Average seasonal pattern of Australian rainfall, illustrated by the monthly mean rainfall for October (spring), January (summer), April (autumn) and July (winter).



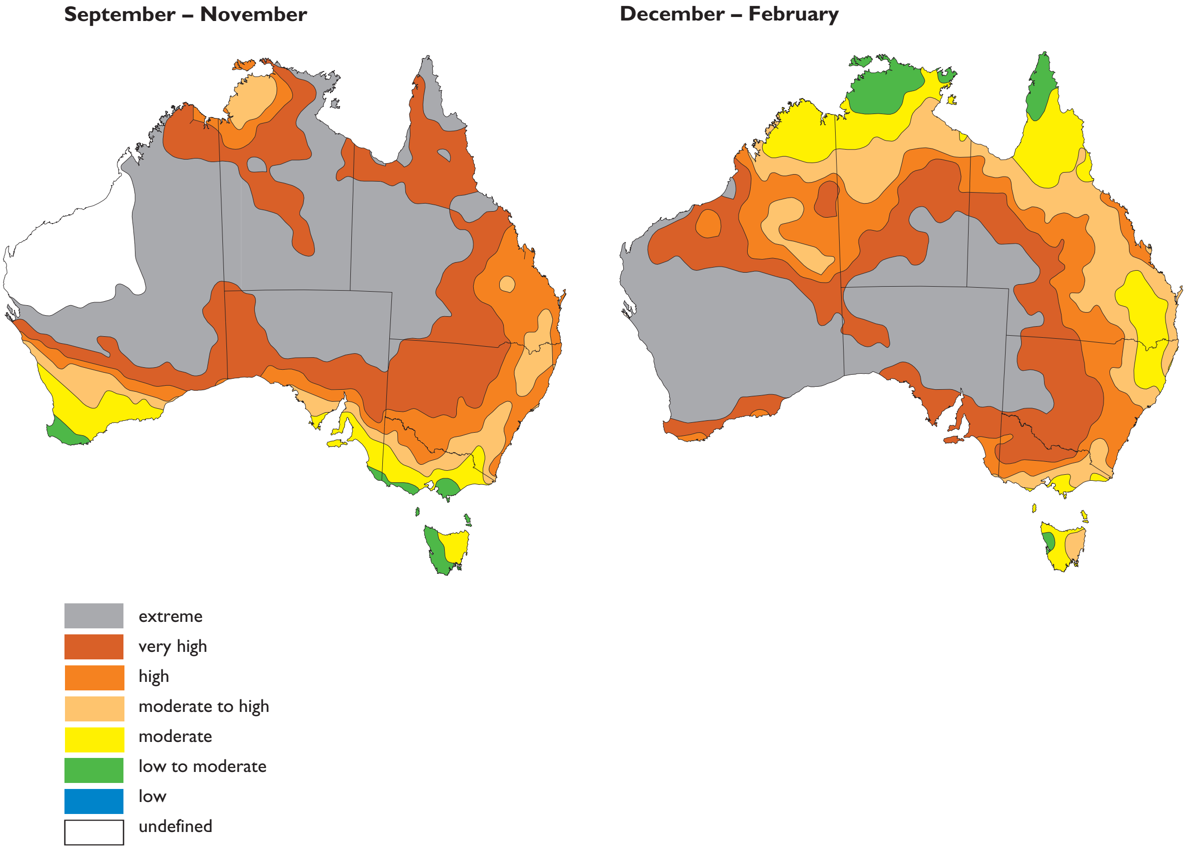
Source: Bureau of Meteorology.

Australia's seasonal pattern of rainfall has a 'flip-flop' character—it is wet in the tropics and dry in the south during the southern summer, and the reverse occurs in the southern winter.

Rainfall variability from year to year is linked with changing currents and water temperatures in the Pacific, Indian and Southern oceans, with a significant correlation between annual continental rainfall and the El Nino – Southern Oscillation phenomenon in the Pacific Ocean.

Distribution of rainfall is strongly non-uniform—approximately one third of the continent is classed as arid and another third as semi-arid. Yearly variation is also very high by global standards (Figure 1.9), with Australia's climate being punctuated by extreme meteorological and associated events (droughts, floods, fires, frosts, dust storms).

Figure 1.9 Variability of Australian rainfall, for September–November (spring), December–February (summer), March–May (autumn) and June–August (winter).



September – November

December – February

Source: Bureau of Meteorology.

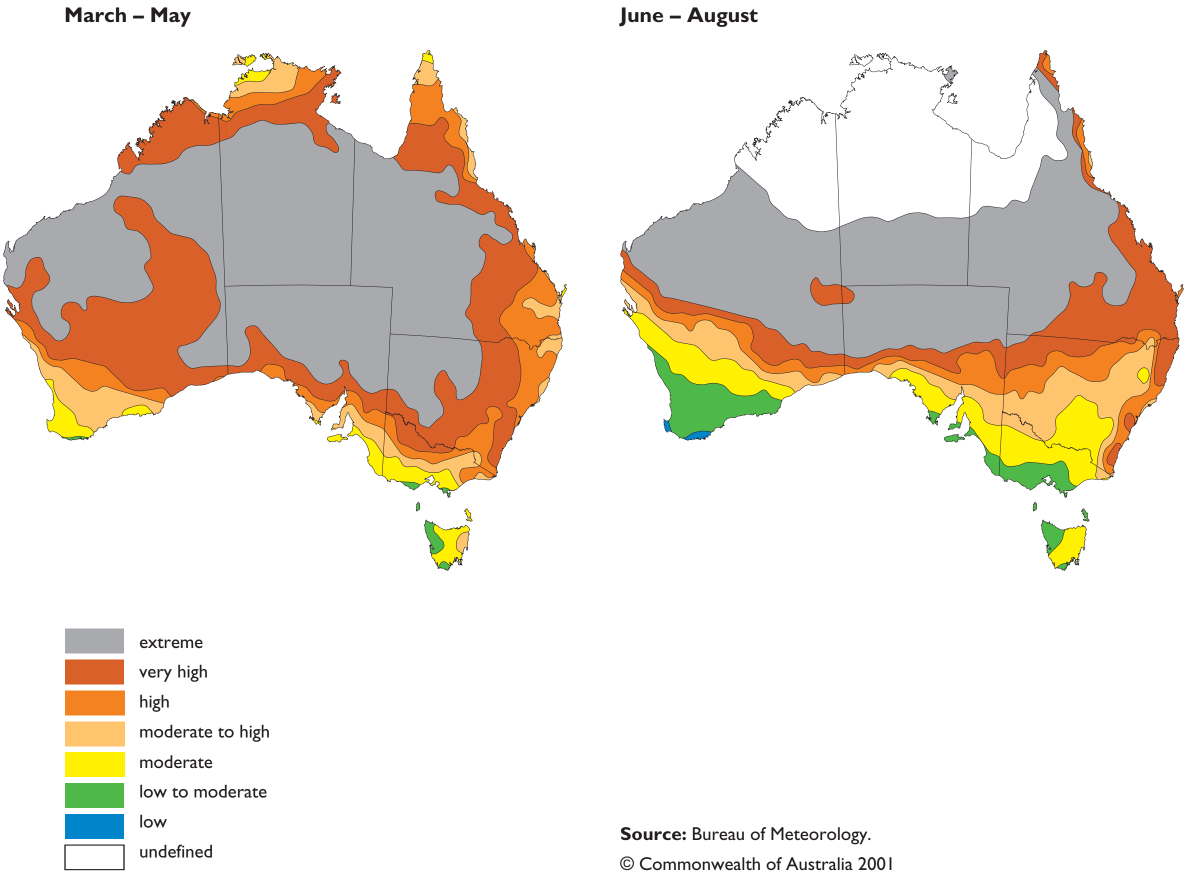
Temperature, humidity and evaporation

In southern Australia, temperatures are cold to mild in winter and warm to hot in summer. In the north, daytime temperatures are continuously warm to hot. Inland semi-arid and arid regions are subject in summer to some of the world's hottest conditions (air temperatures over 50°C and surface temperatures up to 80°C).

Humidity decreases strongly with distance from the coast, and follows the same 'flip-flop' seasonal pattern as rainfall. Only along the southern coast in winter and tropical regions in the wet season is the air truly humid; elsewhere relative humidity is moderate (near the coast) to low (inland).

Potential or free-water evaporation over the Australian continent is generally high, significantly exceeding rainfall in all but the wettest areas. Significant run-off is therefore confined to these wet areas.

Figure 1.9 Variability of Australian rainfall, for September–November (spring), December–February (summer), March–May (autumn) and June–August (winter).



Source: Bureau of Meteorology.

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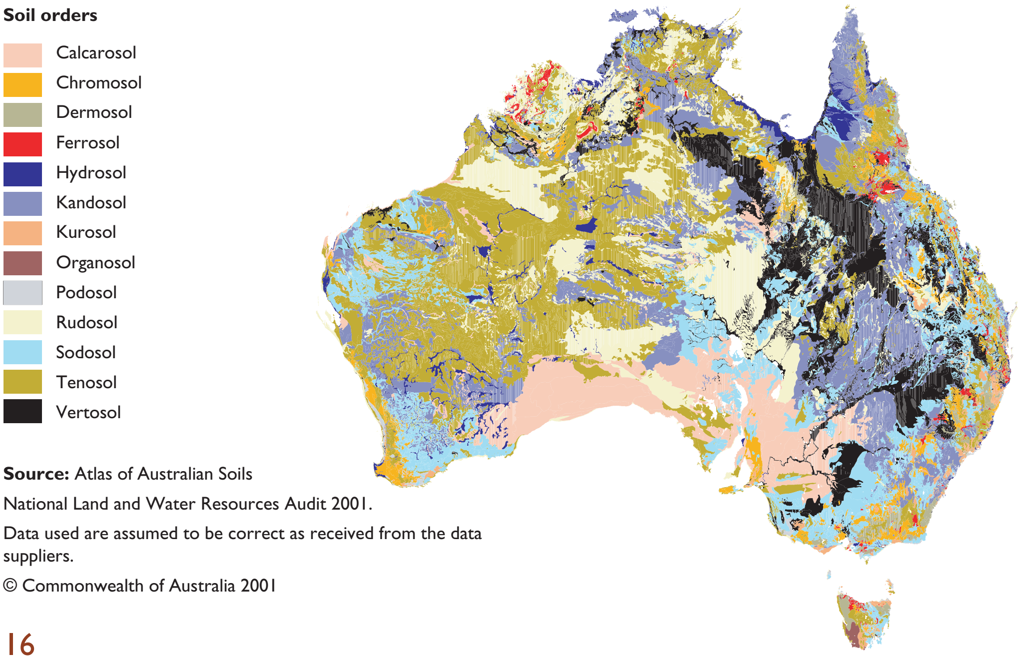
SOILS USED FOR AGRICULTURE

Australia's agricultural landscapes support a great range of soils. Most are ancient, strongly weathered and infertile by world standards. Those on floodplains are younger and more fertile. This variety along with the natural limitations of many soils and their interactions with climate, have made it difficult to develop sustainable agricultural systems. Productivity is also limited by human impacts on soils and while some forms of degradation (e.g. nutrient deficiencies) can be corrected, others are either irreversible (e.g. soil erosion) or difficult to remedy (e.g. subsoil acidity).

Australian soils have many distinctive features:

- soils with surface layers containing low organic matter content are often poorly structured—a condition made worse by various agricultural practices;
- soils with subsurface layers that have a sharp increase in clay content are widespread (Kurosol, Chromosol and Sodosol soil orders [see Figure 1.10]) and can restrict drainage and root growth. These soils also commonly have bleached layers with very low nutrient levels;
- soils affected by salt, either now or in earlier geological times, cover large portions of the arable lands of the continent (Sodosols) and have various nutrient and physical limitations;
- cracking clays that are relatively fertile but exhibit physical limitations (Vertosols) cover very large areas;
- soils formed in aeolian sands (Rudosols and Tenosols) fringe the southern cropping lands, but are more extensive in the arid zone; and
- the remaining ancient land surfaces (particularly in northern Australia) that have very deep and strongly weathered soils (Kandosols) with very low levels of nutrients.

Figure 1.10 Australia's soil orders according to the Australian Soil Classification.



Source: Atlas of Australian Soils

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Table 1.2 Broad overview of the distribution and use of Australia's major agricultural soil types using Australian Soil Classification Orders (million hectares).

	Natural[a]	Production from native pasture[b]	Dryland agriculture[c]	Horticulture	Irrigated agriculture[d]	Other[e]	Total
Calcarosol	23.89	41.9	3.7	0.05	0.04	0.8	**70**
Chromosol	2.78	15.6	4.3	0.04	0.06	0.2	**23**
Dermosol	3.6	7.3	0.9	0.02	0.06	0.2	**12**
Ferrosol	1.6	3.9	0.6	0.02	0.02	0.1	**6**
Hydrosol	5.3	6.5	0.4	0.01	0.02	4.4	**17**
Kandosol	31.9	89.9	5.1	0.02	0.11	0.7	**128**
Kurosol	2.0	3.4	1.0	0.02	0.03	0.2	**7**
Organosol	0.7	0.1	< 0.1	0.00	0.00	0.1	**1**
Podosol	1.0	0.9	0.6	0.01	0.02	0.2	**3**
Rudosol	64.4	41.7	0.4	0.00	0.01	0.7	**107**
Sodosol	12.2	68.7	16.3	0.07	1.00	1.3	**100**
Tenosol	108.8	88.8	2.8	0.02	0.05	1.4	**202**
Vertosol	5.9	75.0	5.2	0.04	0.51	1.9	**88**

[a] Conservation and natural environments

[b] Production from native environments

[c] Dryland agriculture and plantations (excluding horticulture)

[d] Irrigated agriculture and plantations (excluding horticulture)

[e] Built environment and other

AUSTRALIA'S SOILS*

Soils with calcium carbonate: Calcarosols

Solonised brown soils, grey-brown and red calcareous soils, calcareous sands

- contain calcium carbonate as soft or hard fragments or as a solid layer
- occur in areas with low rainfall and are used for cereal growing and irrigated horticulture in the south and sparse grazing in the north
- limitations for agriculture include shallow depth, low water retention and wind erosion on the sandier forms. High salinity, alkalinity and sodicity may also be a problem
- soil nutrient deficiencies are widespread

Acidic soils with an abrupt increase in clay: Kurosols

Podzolic soils, soloths, and texture contrast soils

- strongly acid soils with an abrupt increase in clay down the soil profile
- extend from southern Queensland, through coastal and sub-coastal New South Wales to Tasmania; less common in south-west Western Australia

Some of these soils have been cleared and used for dairying on improved pastures; in the higher rainfall areas of New South Wales and Tasmania, Kurosols are used for forestry; small areas in Western Australia are used for cereal growing and support sparse grazing in lower rainfall, woodland areas.

Soils high in sodium and with an abrupt increase in clay: Sodosols

Solodized solonetz, solodic soils, soloths and red-brown earths, texture contrast soils

- have an abrupt clay increase down the profile and high sodium content, that may lead to clay dispersion and unstable soil structure
- seasonally perched water tables are common on these soils due to the structure of the subsoil
- usually associated with a dry climate
- widely distributed in the eastern half of Australia and the western portion of Western Australia
- common land uses include grazing of native or improved pastures for both dryland and irrigated agriculture, and forestry
- usually very hard when dry and are prone to form surface crusts
- dispersive subsoil makes them prone to tunnel and gully erosion

Soils with an abrupt increase in clay: Chromosols

Non-calcic brown soils, red-brown earths and podzolic soils

- have an abrupt increase in clay content down the soil profile
- do not have high levels of sodium and are not strongly acidic in the subsoil
- occur in most districts and are common in the cereal belt of southern New South Wales, Victoria and parts of South Australia; in the tropics, these soils are mainly used for cattle grazing of native pastures.
- have hardsetting surfaces with structural degradation caused by agricultural practices and may have impeded internal drainage

Structureless soils: Kandosols

Red, yellow and grey earths, calcareous red earths, massive sesquioxidic soils

- mostly well-drained, permeable soils, although some yellow and most grey forms have impeded subsoil drainage
- common in all States except Victoria and Tasmania
- used for extensive agriculture in the wheatbelt of southern New South Wales and south-west Western Australia—in the higher rainfall areas they are used for a range of horticultural crops
- most have low natural fertility and land use is restricted to grazing of native pastures
- grazing lands are susceptible to surface soil degradation such as hardsetting and crusting even where grazing intensity is low

---

* Terminology from the *Australian Soil Classification* (Isbell 1996) is used as a frame of reference because of its practical focus. A generalised map of soil orders is provided in Figure 1.10. More detailed descriptions of each of the soil orders are presented in the Appendix 3.

AUSTRALIA'S SOILS*

Weakly developed soils: Tenosols

Lithosols, siliceous and earthy sands, alpine humus soils and alluvial soils, massive sesquioxidic soils, shallow stony soils, and deep sands

- widespread in the eastern half of the continent where vast areas occur as red and yellow sandplains. Large areas also exist in Western Australia and have red loamy soils with a red-brown hardpan at shallow depths
- due to poor water retention, almost universally have low natural fertility and occur in regions of low and erratic rainfall
- mainly used for the grazing of native pastures
- in the better-watered areas, landform prevents cultivation, but limited areas support forestry (east coast and south-west Western Australia)

Structured soils: Dermosols

Prairie soils, chocolate soils, red and yellow podzolic soils, structured sesquioxidic soils

- occur as moderately deep and well-drained soils in the wetter areas of eastern Australia
- may be strongly acid in the high rainfall areas or highly alkaline if they contain calcium carbonate
- support a wide range of land uses including cattle and sheep grazing of native pastures, forestry and sugar cane. Cereal crops, especially wheat, are commonly grown on the more fertile Dermosols

Iron rich soils: Ferrosols

Krasnozems, euchrozems, xanthrozems, chocolate soils, and structured sesquioxidic soils

- have high free iron and clay contents
- occur along the eastern coastline, in northern parts of Western Australia and the Northern Territory
- may be very deep and well drained in high rainfall zones
- land uses include dairying on improved pastures, horticultural crops, some plantation forestry, and sugar cane in Queensland. In northern Australia the shallow and stony soil types support beef cattle grazing
- may be degraded by erosion and compaction caused by cropping practices. May also suffer from acidification despite being amongst the best soils for a wide range of agricultural pursuits

Minimal soil development: Rudosols

Lithosols, alluvial soils, calcareous and siliceous sands, solonchaks, shallow stony soils, and deep sands

- widespread and diverse
- most have few commercial land uses because of their properties or occurrence in arid regions, or both—the largest areas occur in the desert regions of arid central and north-west Australia and support grazing of native pastures
- fertile variants formed in alluvium are used for cropping and improved pastures.
- some dune soils of the Riverine Plain in the Murray–Darling Basin are irrigated for citrus and vines

Shrink and swell clay soils: Vertosols

Black earths, grey clays, brown clays, red clays, and *cracking clays*

- shrink and swell, and crack as the soil dries
- used for grazing of native and improved pastures, extensive dryland agriculture where rainfall is adequate, and irrigated agriculture
- problems of water entry are usually related to tillage practices and adverse soil physical conditions at least partly induced by high sodium in the upper part of many profiles

Soil orders rarely used for agriculture

- other soil types less commonly used for agriculture include Hydrosols (seasonally wet or permanently wet soils), Organosols (organic or peat soils mainly in coastal or alpine regions), Podosols (usually infertile sandy soils with organic materials and aluminium, with or without iron) and Anthroposols (soils resulting from human activity)

Australian Soil Resources Information System

An understanding of the distribution and properties of Australia's natural resource base is fundamental to sound natural resource management. The best Australia-wide coverage of soils information prior to the Audit was the *Atlas of Australian Soils* (at a scale of 1:2 000 000) completed by CSIRO in 1968. This information was inadequate to answer the key natural resource management questions at a scale relevant to regional planning and development. At the time the Audit was initiated many, more detailed regional-scale data sets existed that could be used to compile a revised Australia-wide data set.

The Australian Soil Resources Information System was designed to build a nationally conformable database from the extensive soil point and survey map data that has been collected and collated by the State and Territory agencies since the early 1970s. Much of this information has been collected over the last 10 years through national programs such as the National Landcare Program and more recently the Natural Heritage Trust. The Australian Soil Resources Information System was developed as a joint project between Bureau of Rural Sciences, CSIRO and State and Territory agencies responsible for soil and land management, using the collaborative framework established by the Australian Collaborative Land Evaluation Program.

Soil attributes from the Australian Soil Resources Information System (Table 1.3) are those most commonly required to characterise, model or predict land resource processes that drive plant productivity, measure resource sustainability or control rates of resource degradation.

The soil attributes, lithology and relief maps were prepared to assist the Audit's modelled assessments of water-borne erosion and river nutrient transport, the current and projected extent of soil acidification, and landscape productivity. These are available through the Australian Natural Resources Atlas and Data Library (**see Appendix 2 for a description and map of each attribute**).

Australian Soil Resources Information System

- A set of spatially distributed estimates of soil attributes and their data quality, as gridded (raster) maps of soil properties for topsoil and subsoil. These maps were produced from the collated data sets using several modelling methods (below). These data are displayed on the Australian Natural Resources Atlas and can be downloaded from the Australian Natural Resources Data Library.
- A compilation (from data held by Commonwealth, State and Territory agencies) of 160 000 soil profile data sets into a single standardised database (SITES—Peluso & McDonald 1995) is available from the Audit data library, subject to some licence conditions.
- A compilation (from data held by Commonwealth, State and Territory agencies) of soil and land resources maps at varying scales. The underlying data were used in modelling work undertaken by the Audit. Descriptions are available from the Audit Atlas and Data Library. The data can be obtained only from the original custodians.
- Various ancillary data sets relevant to soils were used to model soil properties, including: 9 second digital elevation model and derived terrain attributes, lithology (derived from geological mapping), climate surfaces, and satellite imagery (Landsat multi-spectral scanner).

Table 1.3 Australian Soil Resources Information System—soil attributes.

Soil attributes	**Units**	**Map availability**	
		Topsoil (layer 1)	First subsoil (layer 2)
River basins containing intensive agriculture			
pH	pH scale 1 to 14	✓	✓
Organic carbon	%	✓	✓
Total phosphorus	%	✓	
Extractable phosphorus (New South Wales and Victoria)	%	✓	
Total nitrogen (derived from carbon:nitrogen relationship)	%	✓	
Texture	texture class	✓	✓
Clay % (prepared from point and map data)	% fine earth fraction	✓	✓
Australia-wide coverage*			
Clay % (prepared from map data only)	% fine earth fraction	✓	✓
Silt %	% fine earth fraction	✓	✓
Sand %	% fine earth fraction	✓	✓
Thickness	metre	✓	✓
Solum depth	metre		✓
Bulk density	g/cm^3	✓	✓
Available water	mm	✓	✓
Saturated hydraulic conductivity	mm/hr	✓	✓
Erodibility	t ha h/ha MJ mm	✓	

* Data quality and accuracy is variable across Australia. Land resource information is more limited in Australia's arid regions.

Achievements of the Australian Soil Resources Information System

Data: product, protocols and quality assurance

- Prepared 27 new data sets of key soil attributes using the best available information
- Demonstrated the use of soil point and polygon data for spatial modelling and prediction of soil attribute over large areas
- Facilitated quality assurance procedures for Australia's soil data, thereby improving the information base.
- Implemented and refined protocols of the Soil Information Transfer and Evaluation System (SITES)
- Identified data quality inadequacies such as geo-referencing, sample bias and lack of representativeness in existing data
- Identified significant new data sets that could be included in the national data set
- Initiated the development of a polygon database and data transfer standard

Tools developed

- Range of methods for estimating soil attributes, appropriate to the availability and accuracy of input data
- Sophisticated spatial analysis procedures and tools for handling a mixture of point and polygon (taxonomic) data.
- Tools for assessing the quality of the spatial predictions of soil properties

Legacy outcomes

- Tool set for preparing future soil attribute maps
- National database of quality soil point data for future applications
- Institutional arrangements (through a partnership of Commonwealth, State/ Territory agencies) to maintain, update and develop new applications using the Australian Soil Resources Information System

Innovation, research and development, have lifted the potential for agricultural productivity (see *Profile of Australian Agriculture* section) imposed by natural environmental constraints. New systems, information and technologies continue to improve farm productivity and respond to market signals. Increased profitability permits increased investments in farm natural resources and infrastructure.

Dryland regions

- Farming inputs are geared to match expectations of yield; they range from being more conservative, lower input systems in the more arid, mixed farming regions to higher input, more diverse rotations in the more climatically reliable regions.

Medium and higher rainfall regions

- Greater opportunities exist for intensifying and diversifying land use and enterprise mixes in these areas. Many farmers are now changing their rotations or systems of land use to produce a range of products that result in achieving greater and more sustained business profits (through more effective use of resources and capturing synergies between rotations); reducing financial risk (through crop diversification) or improving sustainability of the resource base (through reduced exposure to weeds and diseases or soil erosion through the adoption of minimum tillage practices). Examples include changing from wool to prime lamb or beef; undertaking more diversified cropping with less grazing; growing durum wheat, pulses or canola in rotation with traditional bread wheat varieties; introducing higher-input perennial and annual pasture systems and replacing sheep grazing with horticulture.

Irrigated agriculture

- The capacity to increase water supply to plants offers opportunities to increase production or to enter into new systems of land use (e.g. the recent development of a potato industry in the dry southern Mallee regions of South Australia, where previously dryland crop–pasture rotations were used).

With the adoption of new land use systems, comes the need for new farming practices. Research and innovations are usually needed to meet emerging challenges (e.g. herbicide-resistant weeds, fertiliser requirements, tillage systems). Progressive improvements in site-specific management provide future confidence to farmers and enable them to become more sustainable.

Changed systems of land use have occurred in some regions of Australia over the past 20 years, including:

- more intensive and diversified cropping rotations (e.g. the use of oilseed and pulse crops with cereals in the more reliable wheat–sheep zone of southern Australia) accompanied by a range of new soil and crop husbandry practices;
- progressive introduction of higher input to higher return grazing systems in the dairy and higher rainfall grazing regions;
- development of conservation farming in dryland areas of southern Australia, the northern subtropical cropping regions (where a more diverse range of summer crops have replaced long fallows) and sugar cane regions to minimise risks of soil erosion; and
- growth of cattle feedlot systems, centred around regions with reliable supplies of grain and breeding stock.

All new and proven systems of land use are not immediately or universally accepted. Typically, there is a considerable lag delay in adoption.

Impact of agriculture on landscape resource condition

Unintended consequences of changes imposed by agriculture on soil and landscape processes are often insidious, but are now beginning to affect farm productivity and the future sustainability of agricultural landscapes.

- Development of land (e.g. clearing of native vegetation) induces widespread changes to the functioning of natural ecosystems through altering landscape water balance. This in turn alters key soil processes and the quantity of water, sediments and nutrients transported across landscapes to surface water bodies or into groundwater aquifers.
- Improved productivity is often gained by reducing weeds, pests and diseases.

Agriculture inevitably alters the characteristics of the landscape, with modifications generally being more significant where farming intensity or land disturbance is greater (Tables 1.4, 1.5).

The rate at which a particular landscape responds to changing processes varies significantly and movement towards a new equilibrium may not always be positive for productive agriculture (e.g. dryland salinity is the surface expression of groundwater systems adjusting to a new water balance mainly as result of a change in vegetative cover [NLWRA 2001a]). Similarly, accelerated erosion and soil acidification (see later sections) induced by some agricultural practices need to be recognised and minimised.

Table 1.4 Main forms of land degradation, the changes to land properties and processes and the agricultural systems involved, and associated water quality problems.

Formation of acid sulfate soils

Caused by

- change in oxidation status of particular sulfide minerals (mostly iron pyrites) within coastal sediments, inland discharge areas and around weathering rock piles from mining operations.

Generalised type of disturbance and farming practices

- Drainage of sediments exposing sulfide minerals to aerated conditions
- Any agricultural industries—predominantly sugar and dairying—involving clearing and drainage of coastal plains formed on marine sediments containing susceptible sulfide minerals.

Associated water quality problems

- Acidification and release of heavy metal cations from soil clays, including aluminium, iron and manganese; fish mortalities; clogging of wells and aquifers

Management options

- Avoid disturbing/draining coastal wetlands
- Control of water table levels in wetlands
- Exclusion of stock in inland discharge zone
- Apply lime
- Plant salt/acid tolerant perennials

Nutrient loss

Caused by

- Changes in biogeochemical cycles and components of the hydrological cycle
- Soil erosion by wind and water
- Nutrient exports in harvested farm products

Generalised type of disturbance and farming practices

- Alteration of vegetation, particularly perenniality, leaf area index, root depth and total biomass production; harvesting of produce and export beyond the farm and catchment; addition of inappropriate fertilisers on sandy soils or surface application of fertilisers on sloping or irrigated land
- Crops or pasture types selected and rotations (will affect nutrients removed in produce; potential for nutrient leaching beyond the root zone), excess fertiliser application, tillage, residue management and fallowing practices
- All agricultural industries have the potential to cause nutrient loss

Associated water quality problems

- Eutrophication and nitrate pollution where nutrient loss is associated with runoff and/or leaching rather than product export

Management options

- Adopt rotations to optimise legume nitrogen accretion
- Optimise fertiliser applications
- Optimise soil ameliorant applications
- Treat nutritional disorders in livestock
- Forward plan and record fertiliser decisions in rotations
- Use fertiliser decision support systems, which optimise productivity and are environmentally benign

Table 1.4 Main forms of land degradation, the changes to land properties and processes and the agricultural systems involved, and associated water quality problems.

Organic matter loss

Caused by

- Change to total biomass production and biomass return to the soil; chemical transformations following soil disturbance
- Wind and water erosion of top soil

Generalised type of disturbance and farming practices

- Primarily changes to the vegetation, harvesting of produce and produce export beyond the farm and catchment
- Also increased exposure of surface soil and soil disruption causing loss by erosion and/or oxidation
- Selection of crop or pasture type, fertiliser addition; tillage and residue management practices, grazing intensity
- Generally most pronounced in cropping systems (cotton, grains, sugar and horticulture)
- Excessive soil cultivation (e.g. long fallow)
- Increased by irrigation

Associated water quality problems

- Dissolved organic matter

Management options

- Maintain adequate plant residue cover
- Adopt minimum/zero tillage systems
- Adopt stubble retention/incorporation systems
- Avoid cultivating in high erosion risk periods
- Avoid burning stubbles
- Avoid over grazing vegetation
- Match feed supply to stock demand (feed budgeting)

Salinisation

Caused by

- Changes in components of the hydrological cycle, particularly a decrease in the volume of water lost through interception and evapotranspiration and an increase in deep drainage of soil water, where there is a high salt storage in the catchment regolith or groundwater

Generalised type of disturbance and farming practices

- Primarily alteration of vegetation, particularly in perenniality, leaf area index, and root depth
- Crops or pasture type selected (including tree crops) and rotations, fallowing practices, fertiliser application and grazing intensity
- Also practices which affect soil structure—as described below can affect the downward movement of water through the soil
- All agricultural industries have the potential to cause salinity if they are located in catchments with high salt stores in the regolith or groundwater

Associated water quality problems

- Increased water salinity

Management options

- Pasture management: permanently fence off areas/exclude stock
- Install surface/subsurface drains
- Plant perennial pastures and trees/shrubs in recharge areas. Trees also provide shelter belts.
- Introduce lucerne phase farming (where practical)
- Construct reverse interceptor banks
- Optimising dryland and irrigation water use efficiency by plants

Table 1.4 Main forms of land degradation, the changes to land properties and processes and the agricultural systems involved, and associated water quality problems.

Soil loss

Caused by

- Changes in the balances and transfer of energy in the system and in components of the hydrological cycle (e.g. exposure of surface soil results in energy of rainfall no longer being absorbed by vegetation cover and this energy is then available for detaching particles from soil aggregates and transporting them)
- Similarly, for erosion of exposed top soil by wind energy

Generalised type of disturbance and farming practices

- Increased removal of vegetation and exposure of surface soil (exposes soil to the energy of rainfall impact and wind; loss of roots and other soil organic matter reduces cohesion of soil aggregates); increased soil disturbance through cultivation and pressure on soils (primarily from vehicles and implements, sheep and cattle)
- Tillage and residue management practices, crop or pasture type selected, grazing intensity (affects ground cover and soil organic matter), and vehicle and implement characteristics
- Particularly prevalent in cropping industries due to top soil exposure; still an issue for grazing industries

Associated water quality problems

- Increased stream sediment loads, dissolved organic matter and turbidity

Management options

- Plant pastures instead of crops
- Maintain adequate plant residue cover
- Adopt minimum/zero tillage systems
- Adopt stubble retention/incorporation systems
- Avoid cultivating in high erosion risk periods
- Avoid burning stubbles
- Adopt chemical fallowing
- Use contour banks/grassed waterways
- Reduce impact of feral fauna
- Avoid over grazing vegetation. Match feed supply to stock demand (feed budgeting)
- Fence to land class through a developed farm plan
- Avoid grazing erosion-prone areas. Fence these areas
- Adopt drought management strategies-destocking
- Paddock feedlots, fodder conservation
- Intensive strip grazing/cropping
- Improve degraded riparian buffer zones

Table 1.4 Main forms of land degradation, the changes to land properties and processes and the agricultural systems involved, and associated water quality problems.

Soil acidification

Caused by

- Changes in biogeochemical cycles of carbon and nitrogen (increased nitrogen input and loss of nutrients in produce) and in the hydrological cycle (increased leaching of nitrate and soil cations)

Generalised type of disturbance and farming practices

- As for 'nutrient loss' described above. Inclusion of legumes in crops or pastures and types of fertiliser used, and removal of legume hay are particularly important
- Tends to be associated with grain growing and grazing industries (sheep, beef and dairying). However, other industries can be affected

Associated water quality problems

- Some streams have shown a decline in pH attributable to acidification of surrounding soils. The extent of this phenomenon is unknown

Management options

- Apply liming materials/lime pellet seed
- Grow acid tolerant plants
- Minimise use of ammonium-based fertilisers
- Minimise nitrate leaching by improving water use efficiency
- Sow crops early
- Plant perennials
- Feed hay where harvested
- Adopt reduced tillage and stubble retention
- Spread sodic clays

Subsoil acidity

- Deep soil ripping and lime
- Lime slotting
- Application of calcium enriched materials

Soil structure decline

Caused by

- Processes can operate on top soils and subsoils and include excessive and/or inappropriate tillage, soil compaction by machinery and livestock, poor soil drainage, sodic soil conditions, depleted soil organic matter, exposure of hard setting topsoil by overgrazing or soil erosion

Generalised type of disturbance and farming practices

- Disturbances and farming practices involved as for 'soil loss'
- Risk factors include the use of heavy machinery in cropping industries involving cultivation—cotton, grains, sugar and some horticultural industries and overgrazing

Associated water quality problems

- Indirectly affects water quality through the potential for increased erosion

Management options

- Increase soil organic matter content
- Adopt green trash blankets (sugar cane)
- Grow more pastures in cropping rotations
- Encourage grasses (extensive root systems)
- Apply gypsum (calcium input)
- Adopt reduced/zero tillage. Use chemical fallow
- Adopt stubble retention systems
- Adopt controlled traffic lines in cropped land
- Change grazing management

Table 1.4 Main forms of land degradation, the changes to land properties and processes and the agricultural systems involved, and associated water quality problems.

Waterlogging

Caused by

- Primarily changes in components of the hydrological cycle, particularly a decrease in the volume of water lost through interception and evapotranspiration; waterlogging can also result from a decrease in soil permeability of subsoil layers (plough pans)

Generalised type of disturbance and farming practices

- Disturbances and farming practices involved as for 'salinisation' Plant growth is markedly reduced
- All agricultural industries have the potential to cause waterlogging if they are located in low topographic positions within landscapes

Associated water quality problems

- Changes in redox potential of the soil can result in release of acid drainage, dissolved organic carbon and other compounds to streams, rivers and reservoirs with significant effects on water quality

Management options

- Soil drainage or upslope water interception and diversion schemes
- Rotationally graze or destock affected areas

Table 1.5 Other issues faced in agricultural landscapes.

Occurrence of chemical residues

Caused by

- Introduction of new chemicals to the soil environment

Disturbance

- Application of primarily fertiliser (including sewage effluent and sludges) and pesticide or herbicide applications

Associated water quality problem

- Chemical pollution

Associated agricultural industries

- All intensive agricultural systems utilising fertilisers, pesticides and herbicides. Severity of residue problems depends partly on chemical or fertiliser composition, and application methods, rates and timing

Loss of flora and fauna

Caused by

- Direct change to land properties (vegetation) rather than to processes; secondary loss can result from land degradation processes

Disturbance

- Alteration of vegetation, particularly species composition and vegetation structure

Farming practices causing change

- Clearing, grazing intensity, changing fire regimes, types of crops and pasture types selected

Associated water quality problems

- Loss of riparian vegetation that can affect the light and temperature regime of the adjacent water body; this can also affect nutrient input from litter and the structure of habitat (e.g. loss of woody vegetation which has provided ‘snags’)

Associated agricultural industries

- All agricultural industries; loss is particularly associated with cropping industries (cotton, grains, horticulture and sugar) due to the extensive clearing that has taken place

Weed establishment

Caused by

- Increased light at soil surface; human-aided introduction of weed seeds can be important with some species

Disturbance includes

- Change in condition, connectivity and abundance of native flora and/or fauna
- Exotic weeds hosting root diseases

Farming practices causing change

- Trafficking by animals and vehicles, tillage, grazing intensity, import of livestock, and crop and pasture seeds

Associated water quality problems

- Changes in riparian vegetation through weed establishment affecting light and temperature regimes of the adjacent water body; it can also affect nutrient input from litter

Associated agricultural industries

- All agricultural industries since they aid weed establishment; severity of the weed problem depends on climate and soil type (potential for particular weeds to establish), and eradication programs

RESOURCE SUSTAINABILITY AND STEWARDSHIP

The Standing Committee of Agriculture in Australia defined sustainable agriculture as:

> '*the use of farming practices and systems which maintain or enhance the economic viability of agricultural production; the natural resource base; and other ecosystems, which are influenced by agricultural activities*'
>
> SCA 1991

The guiding principles for sustainable agriculture were stated as:

- farm productivity is sustained or enhanced over the long term;
- adverse impacts on the natural resource base of agricultural and associated ecosystems are ameliorated, minimised or avoided;
- residues resulting from the use of chemicals in agriculture are minimised;
- the net social benefit derived from agriculture is maximised; and
- farming systems are sufficiently flexible to manage risks associated with the vagaries of climate and markets.

These succinct definitions imply the need to manage agricultural systems to be both profitable and environmentally sound, through adoption of efficient and environmentally benign management practices.

Agricultural industries are confronting issues of resource degradation, following a 200 year 'experiment' in land use. Earlier, short term economic gains must now be measured against longer term resource degradation and the costs of repairing rural landscapes (Lovering & Crabb 1998). Continuing investments are needed to develop more sustainable farming systems and to minimise or arrest their continued impacts into the future.

Agricultural industries and farming communities have responsibilities to ensure that land is maintained or enhanced for future generations and that land use impacts are not transferred to the wider catchment or downstream. Importantly, many agricultural industries and their supporting service industries have either established or are moving towards establishing codes of practice which promote quality assurance in the agricultural sector—quality on-farm resource management and delivery of safe food and fibre products to markets—a process that could be styled *product stewardship.*

Renewed emphasis and farmer participation in Landcare and implementing property management plans are most positive signals. Over the last decade, Government initiatives, such as Landcare, encouraged rural communities and individual landholders to become more aware of and to participate in the conservation and repair of natural resources in their regions. In all States, community led catchment management bodies have also worked to plan and implement actions to ensure that significant resource issues are identified and their impacts minimised. Such initiatives are all about *resource stewardship*, defined by Roberts (1990) as:

> *…the act of being entrusted with the management of another's property. With regard to land, this implies that the manager of the land... acts as a trustee on behalf of all the community, with the land managed responsibly and held in perpetual trust for future generations. Management must be equated with stewardship… Stewardship means that present land users …are trustees, not end-users.*

Announcement of the National Action Plan for Salinity and Water Quality in late 2000 signifies that Australia is poised to tackle such critically important and complex natural resource management issues at national and regional scales.

Scope of the Australian Agriculture Assessment 2001

Australian Agriculture Assessment 2001 focuses on natural resource issues in areas containing intensive agriculture. However, this report should also be read in the context of water balance and land management issues discussed in Australian Dryland Salinity Assessment 2000 (NLWRA 2001a) and water use and water availability reported in Australian Water Resources Assessment 2000 (NLWRA 2001b). The impact of all land uses on Australia's native vegetation, catchments, rivers and estuaries from an ecological perspective are also reported in other Audit reports.

Australian Agriculture Assessment 2001 concentrated on soil and land degradation issues most significant to the future viability and sustainability of agriculture. The issues selected for assessment were those induced by agriculture and for which there is some scope or capacity to manage or minimise. Australian Agriculture Assessment 2001 presents:

- shows how and to what extent agriculture has **changed water and nutrient balances**;
- assesses **nutrient inputs and outputs from agriculture** and the implications for nutrient management on-farm;
- forecasts the impact of **soil acidification** on agricultural soils and productivity;
- presents the first comprehensive assessment of **water-borne erosion** and **sediment transport** for Australia's agricultural catchments and rivers and highlights implications for soil, river and estuary management;
- presents **river nutrient budgets** and changes for nitrogen and phosphorus;
- describes characteristics of **Australia's soils** that influence production, and soil and landscape processes;
- highlights the **progress of agricultural industries** in meeting natural resource challenges; and
- identifies key components of **land condition monitoring** so that natural resource changes and outcomes can be measured in the future.

The socioeconomic dimensions of agriculture are reported in a companion to Audit report—*Australians and Natural Resource Management 2001*. This report details the economic benefits that agriculture delivers to the Australian economy and the costs of resource use, particularly off-farm.

Soil issues not addressed by Australian Agriculture Assessment 2001

Other soil-based issues, while not assessed by the Audit (based on stakeholder priorities, time and resources available and/or availability of Australia-wide data) remain important considerations for integrated farm and catchment management. These issues are listed below, with recent Australian reviews or assessments:

- wind erosion (to be reported in *Australian State of Environment 2001*);
- soil sodicity (Naidu et al. 1996, Fitzpatrick et al. 1994);
- soil structure decline (Chan & Pratley 1998, Reeves et al. 1998)
- soil waterlogging except that associated with dryland salinity (Reeves et al. 1998);
- soil water repellence (Doerr et al. 2000; Harper et al. 2000);
- acid sulfate soils (White et al. 1998);
- soil contaminants (Kookana et al. 1998; McLaughlin et al. 1996); and
- soil biological health (Pankhurst et al. 1994).

REFERENCES

Anon 1999, *Ord River Irrigation Area, Kununurra Western Australia* (sixth edition) Agriculture, Western Australia Bulletin 4369.

Chan K.Y. & Pratley J. 1998, 'Soil structural decline- can the trend be reversed?' in *Agriculture and the environmental imperative*', J. Pratley & A. Robertson (eds), pp. 129–63, CSIRO Publishing, Melbourne.

Doerr S.H., Shakesby R.A., Walsh R.P.D. 2000, 'Soil water repellency: its causes, characteristics and hydro-geomorphological significance', *Earth-Science Reviews* vol. 51, pp. 33–65.

Fitzpatrick R.W., Boucher S.C., Naidu R. & Fritsch E. 1994, 'Environmental consequences of soil sodicity', *Australian Journal of Soil Research* vol. 32, pp. 1069–93.

Harper R.J., McKissock I., Gilkes R.J., Carter D.J. & Blackwell P.S. 2000, 'A multivariate framework for interpreting the effects of soil properties, soil management and landuse on water repellency', *Journal of Hydrology* vol. 231, pp. 371–383.

Isbell R.F., 1996, *Australian Soil Classification. The Australian Soil and Land Survey Handbook series*, CSIRO Publishing.

Kookana R.S., Baskaran S. & Naidu R, 1998, 'Pesticide fate and behaviour in Australian soils in relation to contamination and management of soil and water: a review', *Australian Journal of Soil Research* vol. 36, pp. 715–64.

Lovering J.F. & Crabb P. 1998, 'Australia's 200-year experiment in agricultural sustainability', *Agricultural Science* vol. 11, pp. 17–25.

McLaughlin M.J., Tiller K.G., Naidu R. & Stevens D.P. 1996, 'Review: the behaviour and environmental impact of contaminants in fertilisers', *Australian Journal of Soil Research* vol. 34, pp. 1–54.

Naidu R., Kookuna R.S., Oliver D.P., Rogers S. & McLaughlin M.J. (eds) 1996, *Contaminants and the soil environment in the Australasia-Pacific region*, Kluwer Academic Publishers, Great Britain.

NLWRA 2001a, *Australian Dryland Salinity Assessment 2000*, National Land and Water Resources Audit.

NLWRA 2001b, *Australian Water Resources Assessment 2000*, National Land and Water Resources Audit.

Pankhurst C.E.P., Doube B.M., Gupta V.V.S.R. & Grace P.R. (eds) 1994, *Soil biota-management in sustainable farming systems*, CSIRO Publishing, Melbourne.

Reeves G., Breckwoldt R. & Chartres C. 1998, *Does the answer lies in the soil- a national review of soil health issues*, Land and Water Resources Research and Development Corporation Occasional Paper No. 17/97.

Roberts R.W. 1990, *Land conservation in Australia-200 year stocktake*, Soil and Water Conservation Association of Australia.

SCA 1991, *Sustainable agriculture*, Standing Committee on Agriculture Technical report no. 36, CSIRO Publishing, Melbourne.

SCARM 1998, *Sustainable Agriculture: assessing Australia's recent performance*, CSIRO Publishing, Melbourne.

White R.E. & Kookana R.S. 1998, 'Measuring nutrient and pesticide movement in soils: benefits for catchment management', *Australian Journal of Experimental Agriculture* vol. 38, pp. 725–43.

LANDSCAPE BALANCES: WATER, CARBON, NITROGEN AND PHOSPHORUS

SUMMARY

- Agriculture has increased productive capacity of agricultural landscapes. This capacity is determined by changes in water and nutrient availability, assessed through: mapping modelled water, carbon and nutrients balances and distribution of the major stores and fluxes; and determining how stores and fluxes respond to changes in agricultural inputs.

  This can be used to infer patterns of nutrient balance across Australia at a landscape scale and allows broad rankings of nutrient use efficiency for regional agricultural land uses at river basin scale. It also provides a basis for determining where action is needed to minimise potential off-farm impacts.

- Net primary productivity (a measure of plant biomass gain) is an integrated measure of the coupled water, carbon, nitrogen and phosphorus balances. Distribution broadly follows rainfall patterns and is also influenced by air dryness, light and agricultural inputs. Net primary productivity strongly controls carbon stores in plants, litter and soil.
- Net primary productivity averages 0.96 Gt of carbon each year for the Australian continent. Nearly 60 Gt of the total *continental* carbon is stored as plant biomass (45%) and soil carbon (55%).
- Agricultural nutrient inputs have increased *continental* net primary productivity by 5%; the mineral nitrogen store by 13% and the mineral phosphorus store by 8%. These increases have occurred over less than a quarter of the continent (since more than 75% of Australia is rangelands, national parks, or other largely natural and intact vegetation).
- Addition of nutrients and the use of legumes and irrigation water has increased agricultural productivity, nearly doubling pre-European stores of carbon, organic nitrogen and organic phosphorus. Soil mineral nitrogen, plant-available phosphorus, and nitrogen and phosphorus concentrations in soil water have also increased by up to a factor of five. These increases are concentrated in southern agricultural regions of Australia.
- Local influences of irrigation on net primary productivity and stores of nitrogen and phosphorus are large, but impacts at continental scale are relatively small.
- Harvested product is relatively small component of the *continental* net primary productivity and landscape stores of carbon, nitrogen and phosphorus. Nutrients applied to agricultural landscapes can exceed those required to achieve optimum production levels and in some regions are approaching diminishing returns. Attention to nutrient balance on farm will lead to more cost-efficient agriculture and fewer off-farm impacts.
- Nutrients leaking from farms can lead to enriched rivers, estuaries and near-shore marine zones. Priority needs to be given to managing farm nutrient inputs more efficiently to counter increasing associated environmental costs.

MASS BALANCES—A BASIS FOR NATURAL RESOURCE ACCOUNTING

The availability of light, water and nutrients determines the capacity of land to produce native vegetation and agricultural yield. In Australia, long-term availability of resources and the consequent potential for generating yield can be assessed by examining the mass balances of the key resources: water and nutrients (in this case nitrogen and phosphorus). Mass balance gives a quantitative picture of:

- resource inflows or sources;
- resource outflows (including both production outputs and unproductive losses or leakages);
- the resource stock (the amount available for use); and
- the way that the stock changes with time in response to the various inflows and outflows.

The mass balances of water and nutrients are linked by carbon (or biomass) since plant biomass is approximately 50% carbon. Balances and cycles of water, nitrogen, phosphorus and carbon interact and constrain each other.

- The rate of plant biomass production determines how much resource is available for harvest and for maintaining natural and farmed animal populations.
- Production of plant biomass is closely linked to plant water use, and is usually a dominant outflow in the landscape water balance.
- Production of plant biomass is linked with uptake of nutrients from soil into plants, after which the nutrients are locally recycled through litter or removed in plant or animal harvest.

The net rate that plants build up carbon from the atmosphere by photosynthesis is known as 'net primary productivity'.

Nutrient balance also depends on several nutrient inflow and outflow processes:

- *nitrogen* inflows include atmospheric deposition and fixation and fertilisation; outflows include gaseous loss (volatilisation and denitrification), leaching beyond the root zone, export in surface run-off, and removal by harvest;
- *phosphorus* (taking account only of the part of the total phosphorus in the soil which is chemically available to plants) inflows include physical or biological weathering which releases phosphorus from soil minerals and fertilisation; outflows include leaching, export in run-off, in both dissolved and sediment-bound forms and removal by harvest.

Each of these processes influences nutrient balance, and it is important to determine their relative effects.

Net primary productivity

'Net primary productivity' is the carbon gained over time by plants through photosynthesis, minus the carbon loss over time through plant respiration. It is a fundamental measure of 'landscape yield' and is expressed in carbon units (e.g. tonnes of carbon per hectare per year).

Net primary productivity is not only significant as a measure of landscape yield, but also because plants acquire carbon from the air and nutrients from the soil in tightly constrained ratios, so that it provides information about the plant–soil cycle of nutrients through growth and decay.

A biophysical balance sheet for any landscape has both spatial and *change over time* variability:

- *spatial variation* is characterised by mapping the major reserves and flows of resources across the continent;
- a first insight into the *changes over time* can be gained by comparing the stocks and flows in the mass balances under 'natural' conditions with the corresponding stocks and flows under agricultural land management regimes. Under agriculture, nutrient inputs may be enhanced by fertilisers or legumes; water inputs may be enhanced by irrigation. Change since European settlement gives an initial estimate of the changes in the biophysical balance sheet brought about by agricultural practices.

The biophysical balance sheet can be used to determine:

- *nutrient use efficiency* from agricultural systems estimates whether nutrient inputs balance outputs or whether there is a net loss or 'mining of available nutrients' or net surplus of nutrients;
- the magnitude of *off-farm nutrient fluxes*—if there is a surplus of nutrients then transport off farm by leaching, in run-off and through soil erosion, can increase the potential for impacts such as algal blooms in rivers, estuaries and near-shore marine zones.

LANDSCAPE FUNCTION AND MASS BALANCES

a summary of methods

Landscape function: understanding the components and pathways

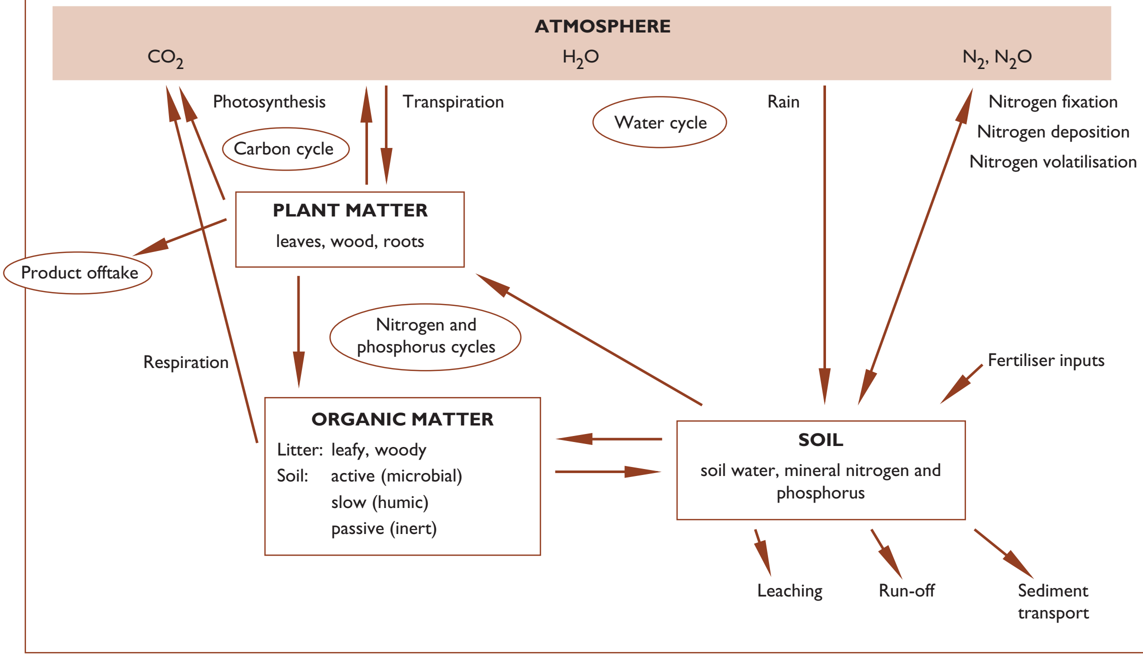
Flows of water, carbon, nitrogen and phosphorus transfer matter through stores or pools (Figure 2.1). The stores include leaves, wood, roots and soil (including the A and B soil horizons). Pools in the soil are further subdivided for modelling purposes to account for components of the carbon, nitrogen and phosphorus stores with different turnover times or chemical reaction properties, representing the active (metabolic), slow (humic) and passive (inert) components of soil organic matter.

Key flows that exchange matter between the pools include:

- conversion of light into plant biomass by photosynthesis;
- local cycling of water through rainfall, soil evaporation and plant transpiration;
- uptake of nutrients by plants and their return to the soil in decomposed litter;
- grazing and nutrient cycling by animals; and
- harvest of agricultural produce.

Cycling can also be internal—local cycling between the stores in the landscape—or between the landscape and its external environment (e.g. cycling energy through light, heat and evaporation; water through rain and evaporation; carbon through photosynthesis and respiration). Landscapes are also subject to inputs and losses of nutrients through atmospheric deposition, fertilisation, fixation, leakage in run-off and leaching, gaseous losses to the atmosphere, and harvest of product.

Figure 2.1 Major pools and fluxes in the linked water, carbon, nitrogen and phosphorus cycles through the atmosphere, plants and soil. Net primary productivity is the sum of photosynthesis and plant (not litter and soil) respiration.



Models for landscape balances

Two models were developed for determining landscape balances of carbon, nitrogen and phosphorus and estimate of change in net primary productivity:

- an evolving or time-dependent model (BiosEvolve); and
- an equilibrium or statistically steady state model (BiosEquil).

Predictions of these models are designed to determine large-scale patterns rather than the behaviour of individual farms or paddocks, and should never be interpreted at single-cell (5 km) scale. Uncertainties even at a large region scale (100 km by 100 km or greater) for the models are:

Net primary productivity:	30%
Organic stores of C, N and P:	50%
Mineral stores of C, N and P	100%
Current/pre-agricultural ratios:	50%
Leaching and drainage fluxes:	large uncertainty

Further information on the methods developed for this landscape scale assessment can be found in the project reports on the Australian Natural Resources Atlas.

Mass balance equations

Water

- Total water *is equal to* plant water *plus* soil water
- Change in water over time *is equal to* rainfall *minus* canopy transpiration, soil evaporation, interception evaporation, runoff and drainage

Carbon

- Total carbon *is equal to* plant carbon *plus* litter carbon *plus* soil carbon
- Change in carbon over time is equal to assimilation minus plant respiration, soil microbial respiration and disturbance
- Change in carbon over time *is also equal to* net primary production *minus* heterorespiratioin and disturbance

Nitrogen

- Total nitrogen *is equal to* plant nitrogen *plus* litter nitrogen, soil organic nitrogen and soil mineral nitrogen
- Change in nitrogen over time *is equal to* fertilisation, fixation and deposition *all minus* volatilisation, leaching, particulate transport, offtake and disturbance

Phosphorus

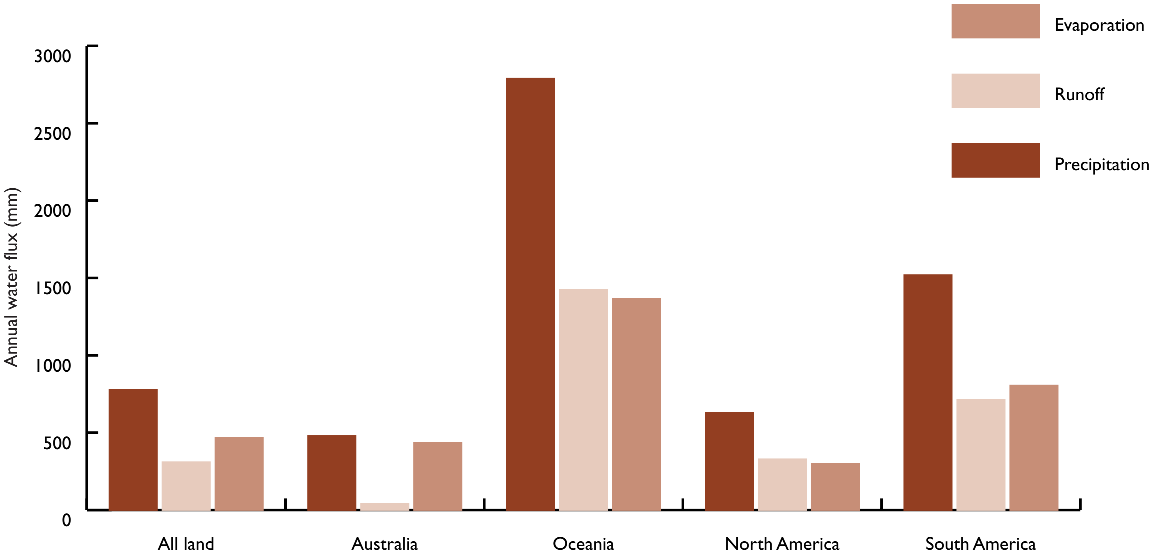
- Total phosphorus *is equal to* plant phosphorus *plus* litter phosphorus, soil organic phosphorus, labile phosphorus and secondary phosphorus
- Change in phosphorus over time *is equal to* fertilisation plus deposition and weathering *minus* leaching, particulate transport, occluded phosphorus sink, offtake and disturbance

It is often true that a store on average neither increases nor decreases (though it fluctuates continually about an average value) over a long time. Time-averaged values of change in storage then approach zero as the averaging time increases. This is the 'statistical steady state' condition.

WATER BALANCE

Australia's overall continental water balance is unusual in global terms (Figure 2.2).

Figure 2.2 Terms in the annual water balance (precipitation = evaporation + run-off) averaged over all land surfaces on earth (left bars) in comparison with the same terms averaged over the continents of Australia, Oceania, North America and South America.

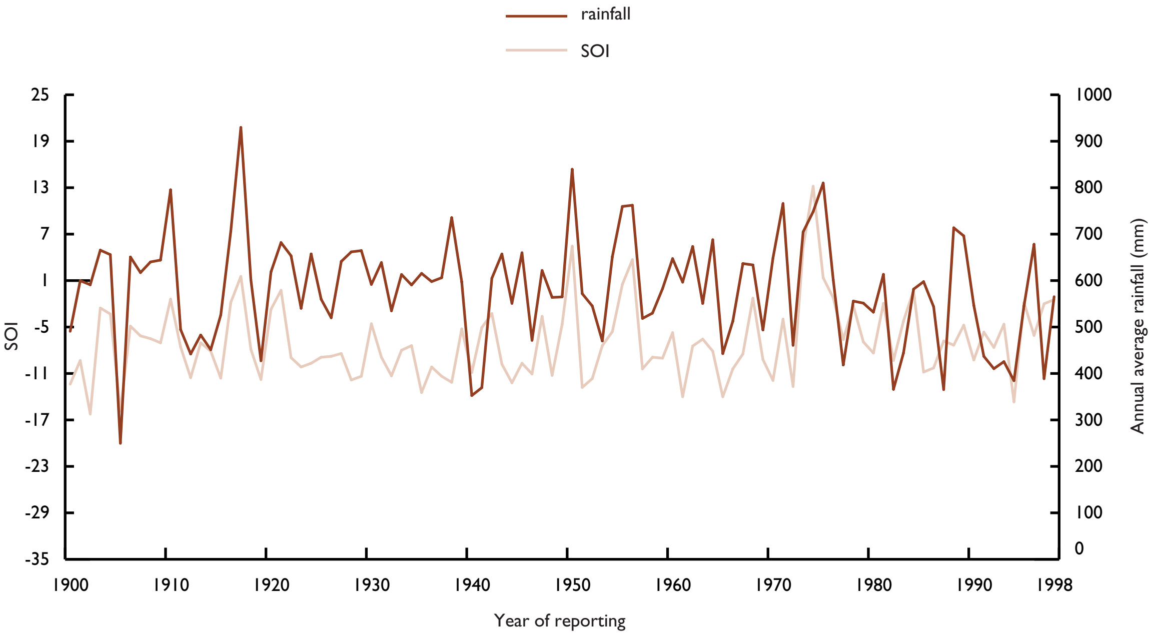


Rainfall

Australia is the driest inhabited continent in the world. It receives an average annual rainfall of 465 mm compared with a global average annual rainfall of 777 mm on land surfaces. Almost all of this is evaporated, leaving only 52 mm of water annually for run-off—much less than the 310 mm of annual run-off averaged over the Earth's land surfaces.

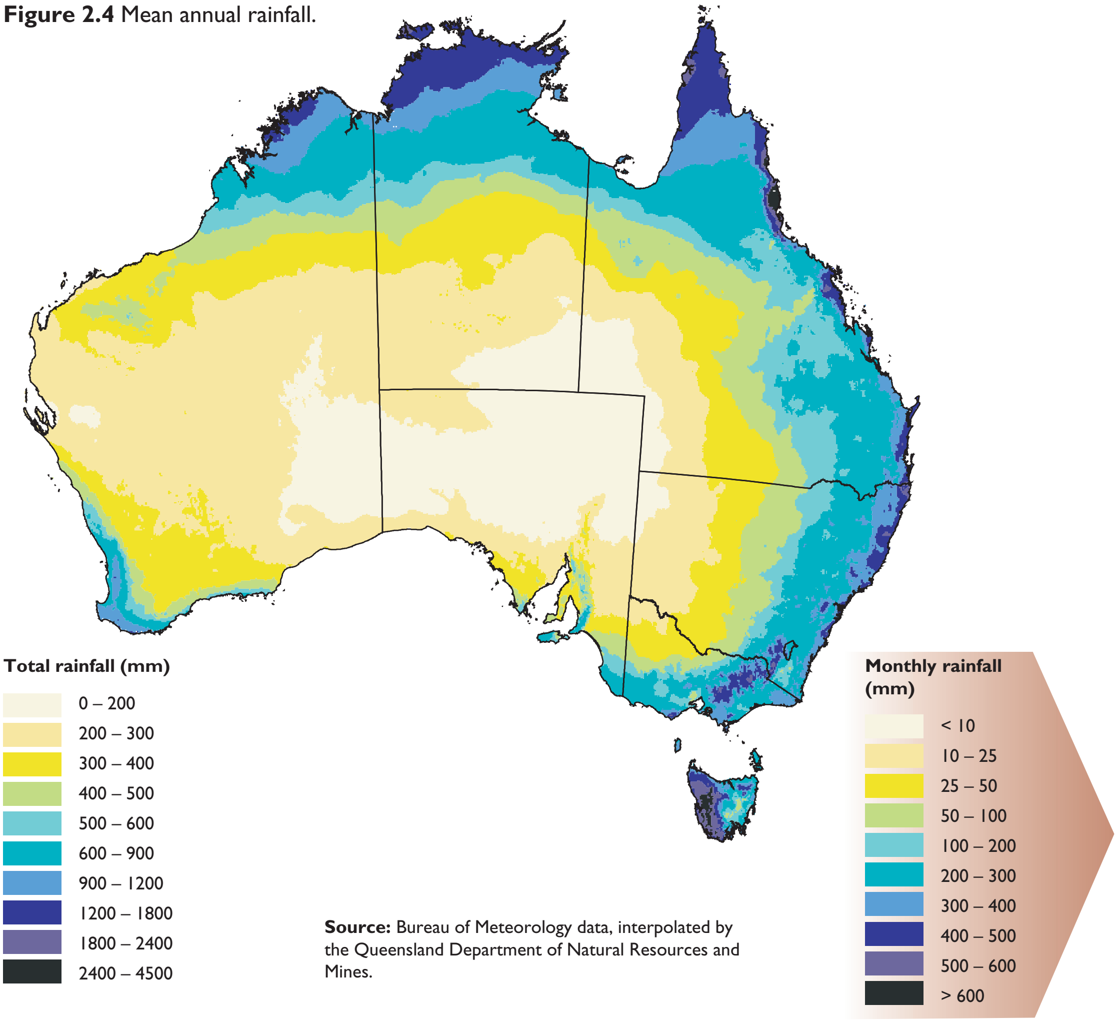
Yearly variation is also very high by global standards and is linked with changing currents and water temperatures in the Pacific, Indian and Southern oceans, with a significant correlation (about -0.5) between annual continental rainfall and the ENSO (El Nino – Southern Oscillation) phenomenon in the Pacific Ocean (Figure 2.3). The ENSO influence is strongest in the north east and weak in south-western Australia.

Figure 2.3 The annual average rainfall over the Australian continent during the twentieth century and the annual average of the Southern Oscillation Index (the normalised difference between atmospheric pressures at Darwin and Tahiti).



Source: Bureau of Meteorology.

Figure 2.4 Mean annual rainfall.



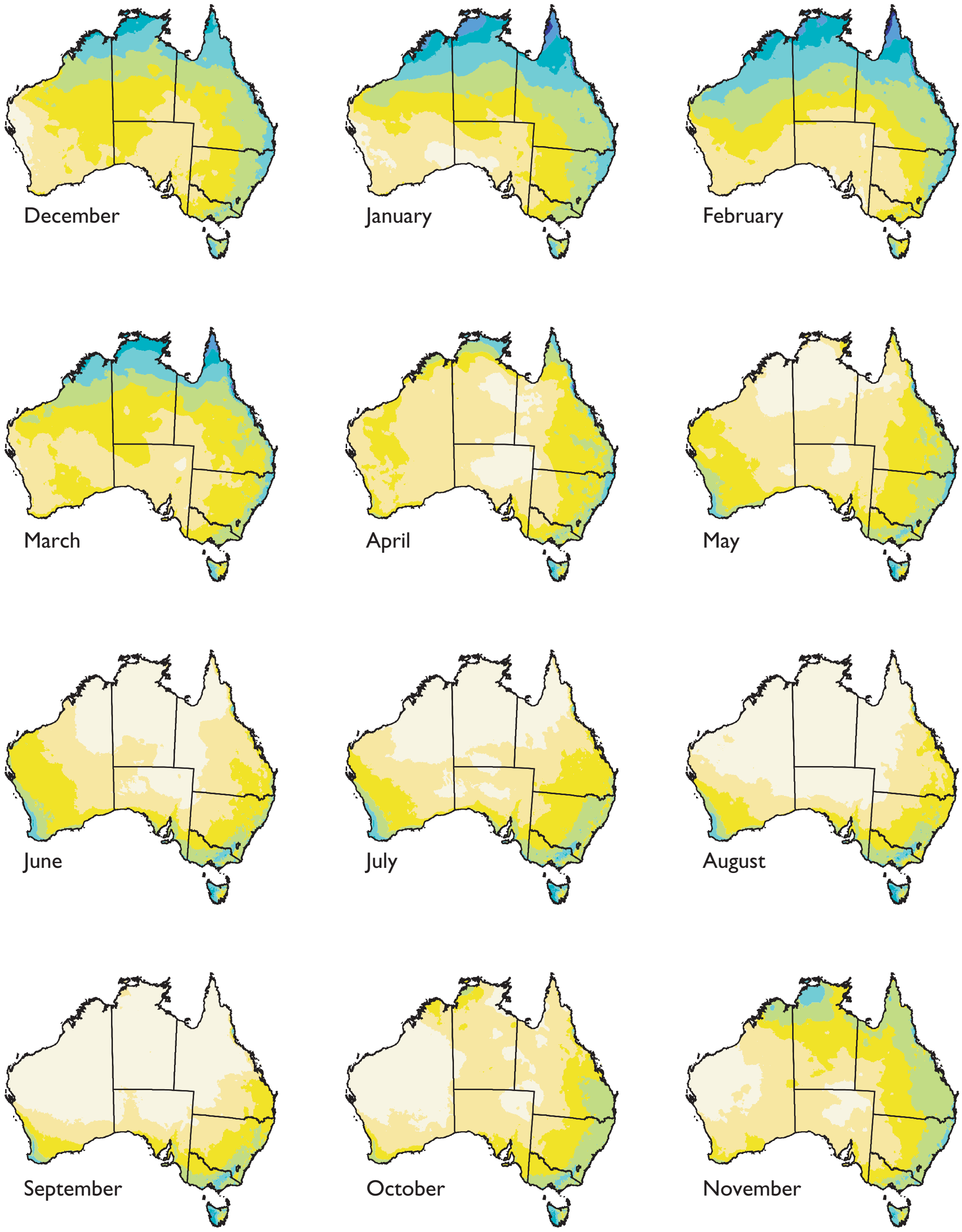
Source: Bureau of Meteorology data, interpolated by the Queensland Department of Natural Resources and Mines.

Distribution of rainfall is strongly non-uniform (Figures 2.4, 2.5). Approximately one third of the continent is classed as arid (receiving less than 250 mm average annual rainfall) and another third as semi-arid (250 – 500 mm).

Australia's seasonal pattern of rainfall has a 'flip-flop' character—it is wet in the tropics and dry in the south during the southern summer, and the reverse in the southern winter.

- Rainfall pattern in the north is dominated by a humid, monsoonal wet season (October to March) followed by a hot, dry season (April to September).
- In the south west, the pattern is Mediterranean with hot, dry summers and cool, wet winters, watered by frontal rain from the Southern Ocean.
- In the south east, rainfall is more uniformly distributed through the year, under the combined influences of winter rain from the Southern Ocean and summer rain from the Pacific Ocean, brought by weather systems from the north east.

Figure 2.5 Mean monthly rainfall (see legend p 42).

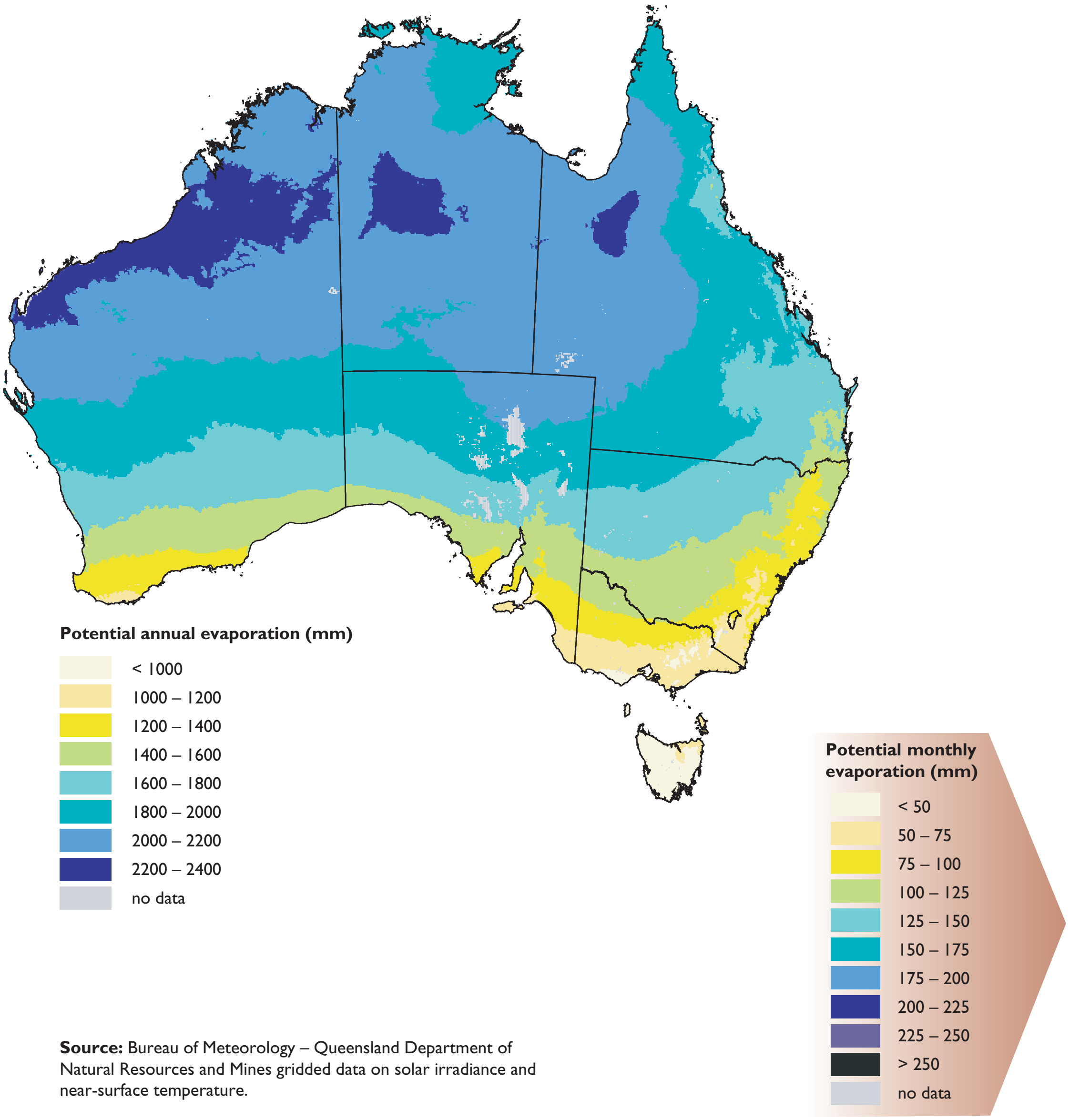


Source: Bureau of Meteorology data, interpolated by the Queensland Department of Natural Resources and Mines.

Evaporation and transpiration

Potential evaporation is high and significantly exceeds rainfall in all but the wettest areas (Figures 2.6, 2.7). It is extreme (approaching 10 mm/day) in the northern inland in summer and decreases with decreasing solar radiation (i.e. in the south, in winter and near to coasts due to increasing cloudiness).

Figure 2.6 Priestley-Taylor (potential) mean annual evaporation.



Source: Bureau of Meteorology – Queensland Department of Natural Resources and Mines gridded data on solar irradiance and near-surface temperature.

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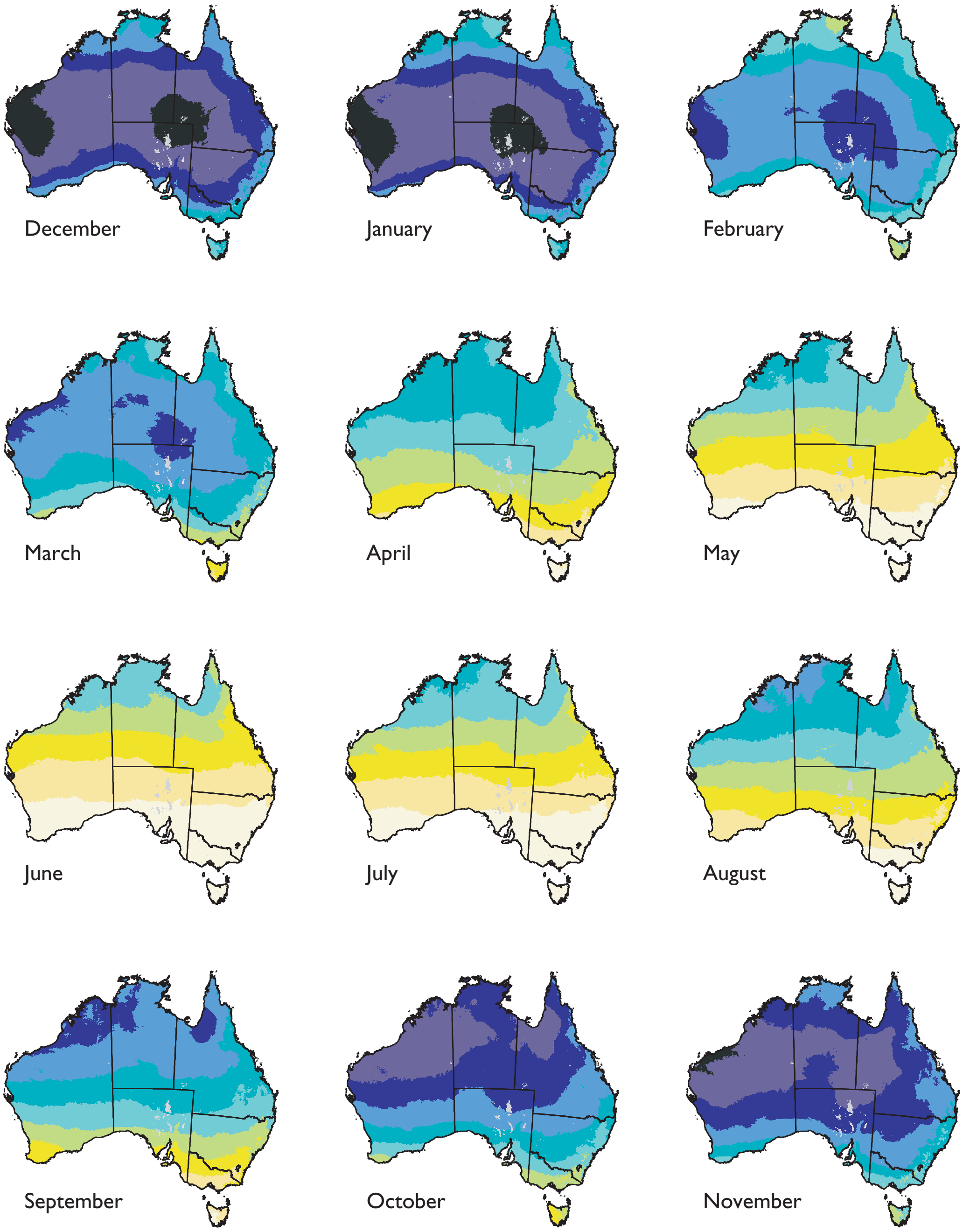
* Potential evaporation is defined as energy-limited or Priestley-Taylor evaporation.

Figure 2.7 Priestley-Taylor (potential) mean monthly evaporation (see legend p. 44).



December

January

February

March

April

May

June

July

August

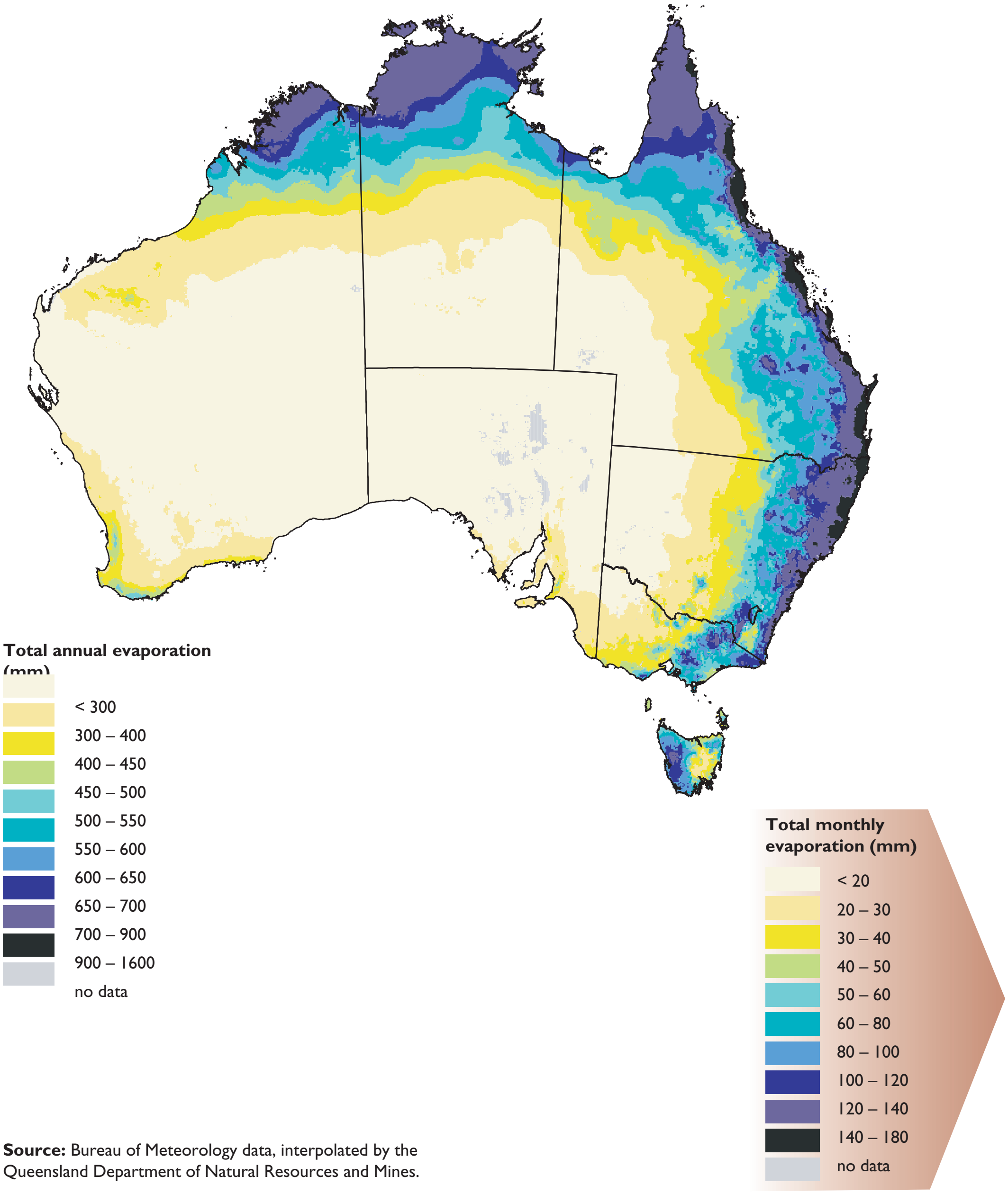
September

October

November

Source: Bureau of Meteorology data, interpolated by the Queensland Department of Natural Resources and Mines.

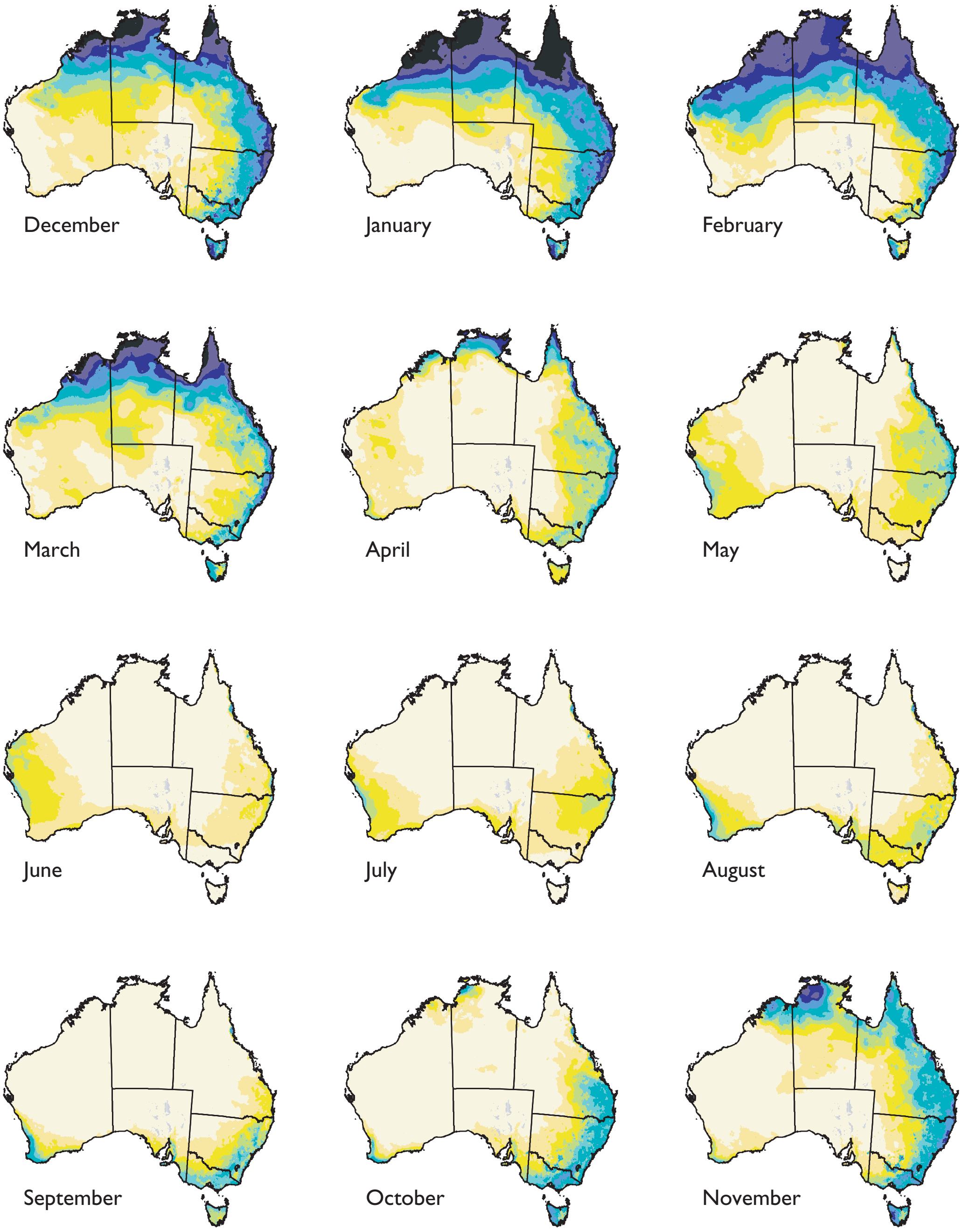
Figure 2.8 Mean annual total evaporation (canopy transpiration plus soil evaporation).



Source: Bureau of Meteorology data, interpolated by the Queensland Department of Natural Resources and Mines.

Actual evaporation (Figures 2.8, 2.9) and transpiration by plants (Figures 2.10, 2.11) are more spatially variable than potential evaporation, reflecting the effects of water limitation in most areas of the continent. Their annual mean and seasonal patterns broadly resemble the patterns for rainfall.

Figure 2.9 Mean monthly total evaporation (canopy transpiration plus soil evaporation) (see legend p. 46).



December January February

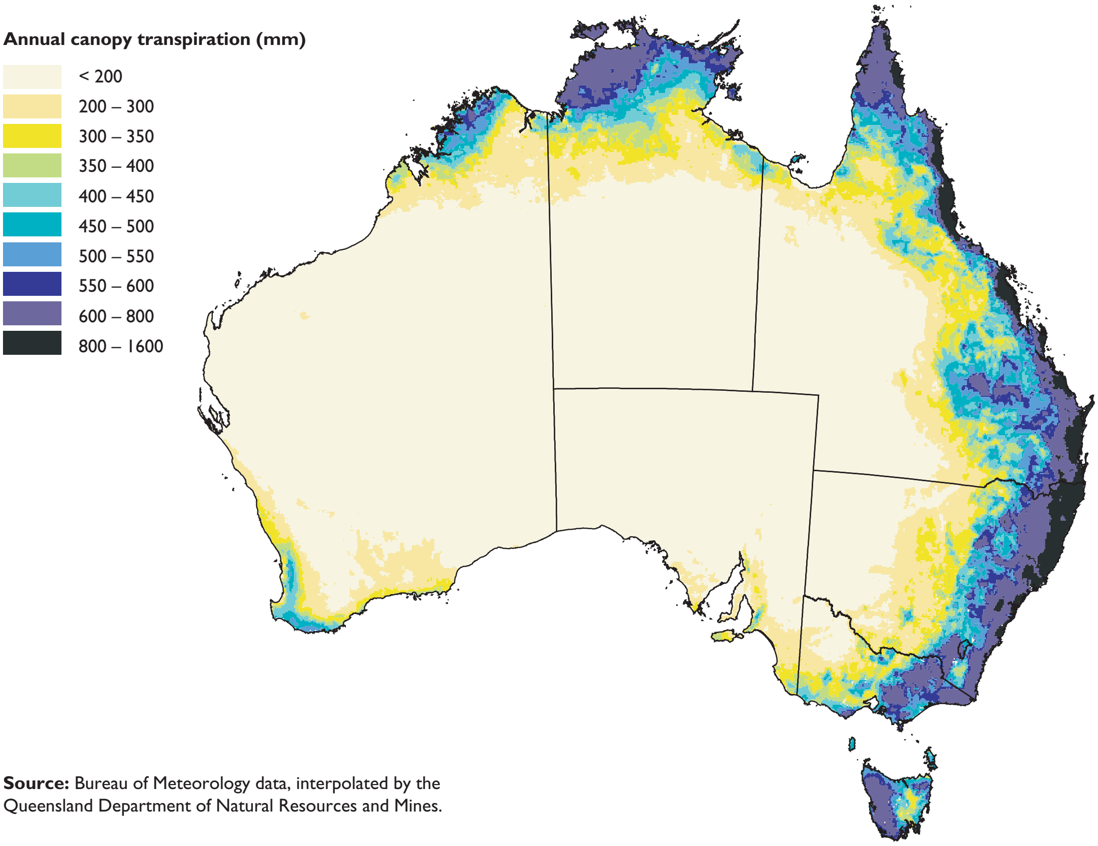
March April May

June July August

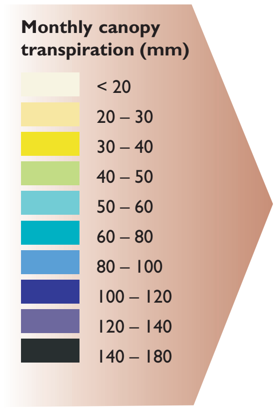
September October November

Source: Bureau of Meteorology data, interpolated by the Queensland Department of Natural Resources and Mines.

Figure 2.10 Mean annual canopy transpiration.

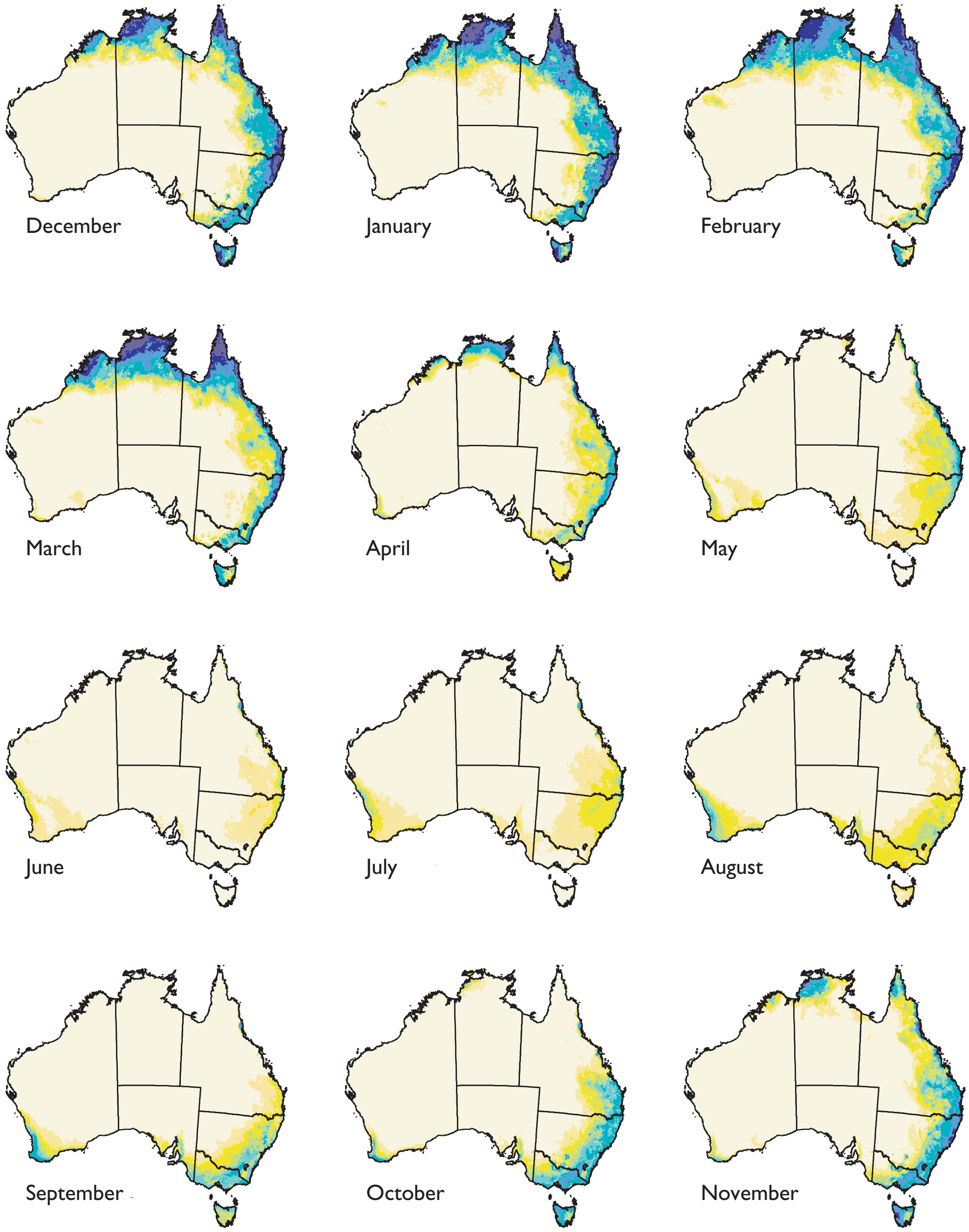


Source: Bureau of Meteorology data, interpolated by the Queensland Department of Natural Resources and Mines.



Soil evaporation is the difference between total evaporation and canopy transpiration and is a large part of the total where plant cover is low (e.g. in arid environments). Hence, canopy transpiration maps have more 'contrast' (relative variation) than the total evaporation or rainfall maps (Figures 2.10, 2.11).

Figure 2.11 Mean monthly canopy transpiration (see legend p. 48).



December

January

February

March

April

May

June

July

August

September

October

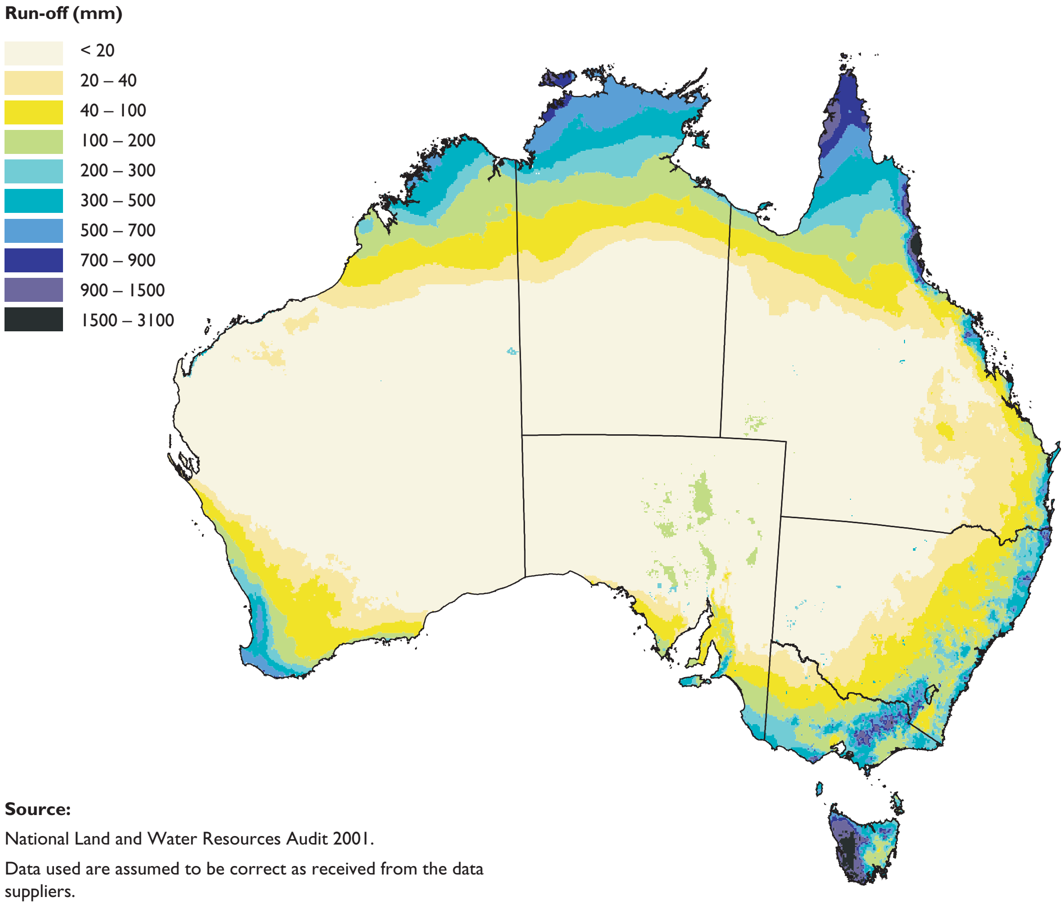
November

Source: Bureau of Meteorology data, interpolated by the Queensland Department of Natural Resources and Mines.

Run-off and drainage

Significant run-off is confined to those wet areas where rainfall significantly exceeds potential evaporation. It occurs only in the south east (including Tasmania), over the eastern ranges and in the north (Figure 2.12). Run-off is negligible in the drier divisions.

Figure 2.12 Mean annual total run-off (surface plus subsurface).

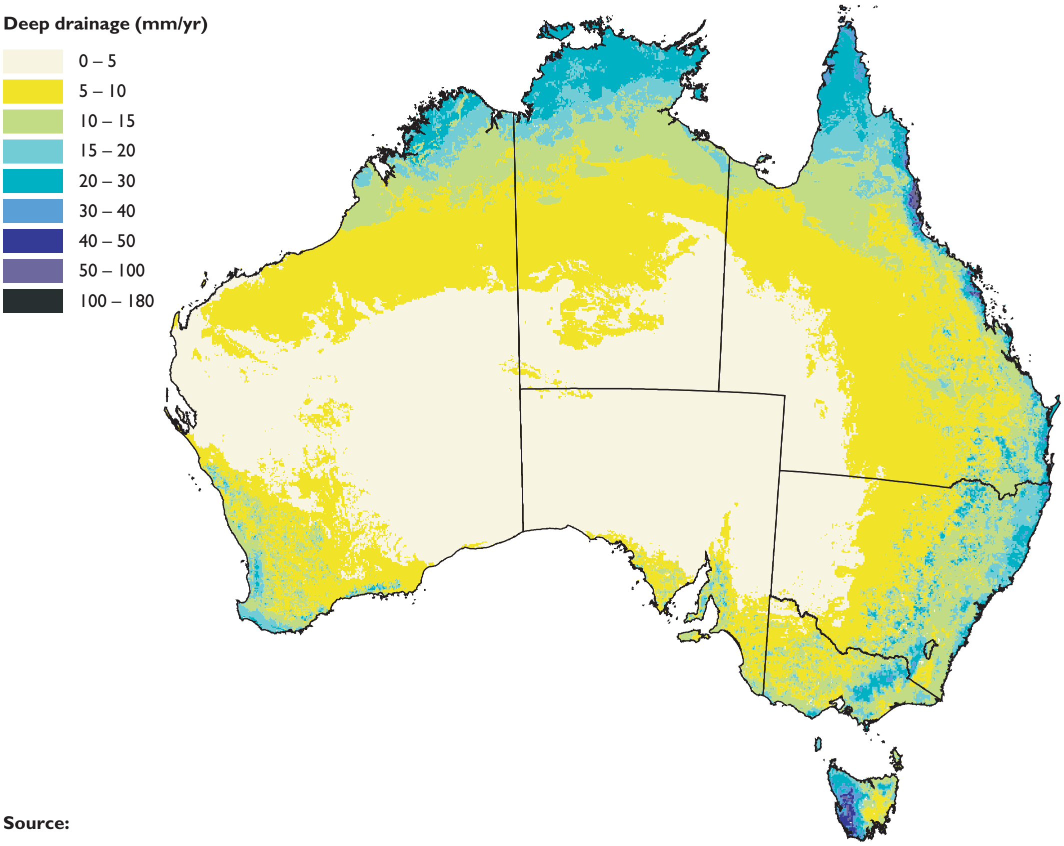


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 2.13 Mean annual deep drainage.

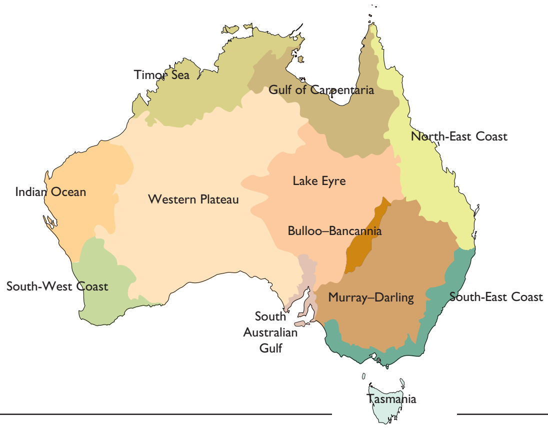


Source:

National Land and Water Resources Audit 2001.

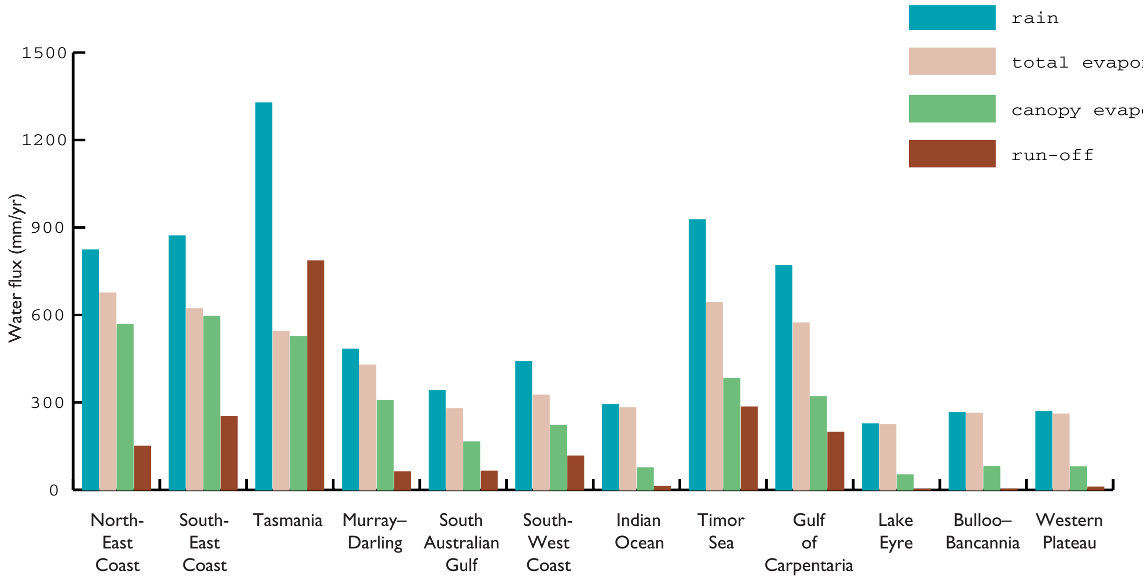
Data used are assumed to be correct as received from the data suppliers.

Drainage has a similar pattern, though with added variability induced through the influence of soil texture (Figure 2.13).



The broad spatial pattern of the entire steady-state water balance can be seen by plotting its constituent terms as spatial averages across each of Australia's 12 drainage divisions (the largest hydrological units for the Australian continent). At this level of aggregation, the water balance is *rainfall* = *total evaporation* + *total run-off*, where total evaporation includes contributions from both canopy and soil and total run-off includes both surface and subsurface routes. Figure 2.14 shows the rainfall, total evaporation and total run-off for the drainage divisions, along with the canopy transpiration. Canopy transpiration is less than half of the total evaporation in the drier Divisions—Indian Ocean, Lake Eyre, Bulloo-Bancannia and Western Plateau.

Figure 2.14 Terms in the time-averaged water balance (rainfall = total evaporation + run-off) averaged spatially across each Australian Water Resources Council drainage division.



Water balance and Australian agriculture

Australian agricultural productivity and sustainability are constrained by rainfall and humidity since water use efficiency of plants decreases as humidity falls. Australian agriculture also has to cope with very high climate variability.

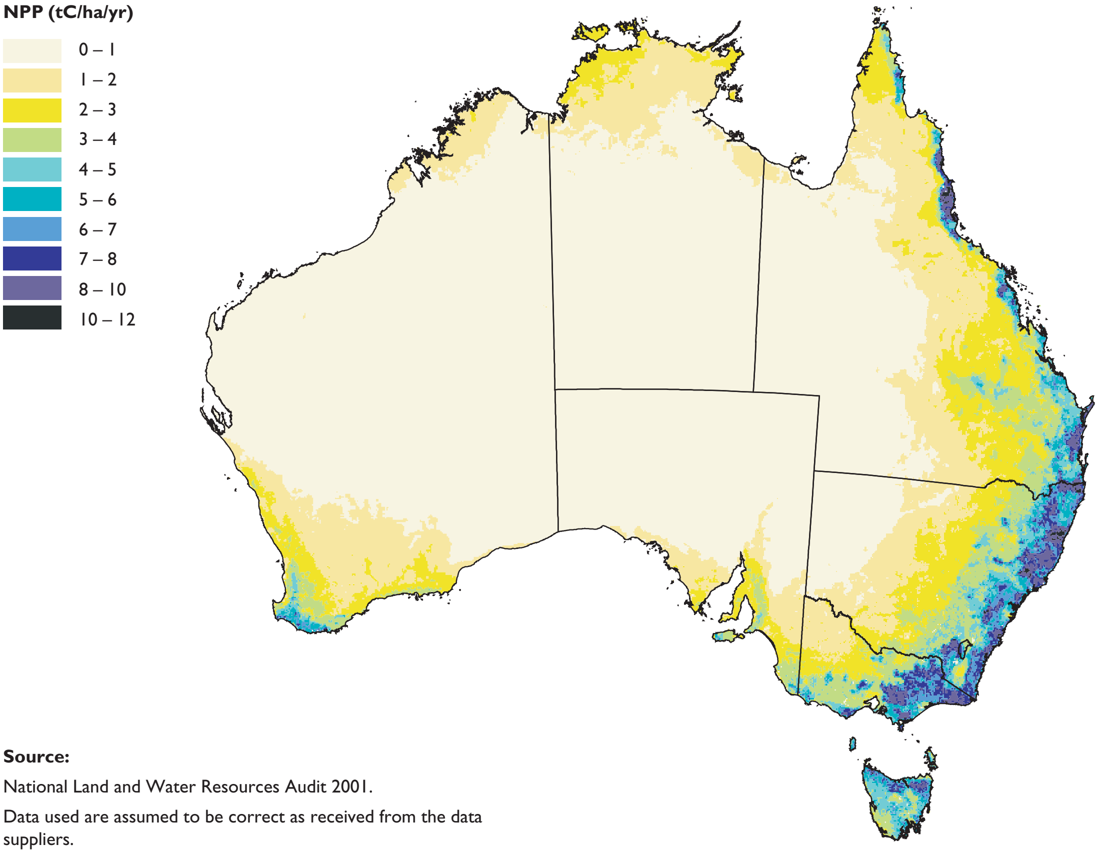
- It needs to be recognised that agriculture is not an option for much of the Australian continent. Therefore, we need to sustainably manage and retain agriculture in good quality, higher rainfall landscapes.
- Australian farming systems need to maximise efficient use of natural rainfall through farming and pasture systems that can respond to and work within the context set by rainfall variability. In areas with waterlogging and dryland salinity, minimising deep drainage beyond the root zone will also be an important consideration. *Australian Dryland Salinity Assessment 2000* (NLWRA 2001) outlines the water balance issues involved in salinity management.
- We need to maximise efficient use of irrigation water supplies to provide a more secure (but still variable) source of water for agriculture. Water use efficiency and sustainable practices are imperative for maximising and sustaining irrigation schemes. We need to minimise deep drainage of water beyond the root zone.
- We need to invest in climate forecasting to provide information that supports farmer decisions (e.g. whether to crop or leave fallow, whether to stock or de-stock). Returns on investment in climate forecasting are likely to be high in terms of both increased productivity and reduced reliance on Exceptional Circumstances Drought Relief.

Landscape yield or net primary productivity

The mean annual net primary productivity, with present agricultural inputs and exports of nutrients off farm together with the increase in production through irrigation, is shown in Figure 2.15. The key role of net primary productivity is determining fluxes and stores in the terrestrial carbon, nitrogen and phosphorus cycles (Figure 2.1). Dominant features of the net primary productivity map are:

- Net primary productivity broadly follows rainfall, but with regional modulation from saturation deficit (or how dry the air is) through its effect on water use efficiency and also, in the case of Tasmania, by light.
- The modulation by saturation deficit implies that there is less net primary productivity per unit rainfall in the north of the continent (where the saturation deficit is high on average, because of high air temperatures) than in the south (where the saturation deficit is lower on average).
- Modulation by light is significant only in Tasmania. Elsewhere, light is not a limiting resource for net primary productivity in Australia.
- The net primary productivity is also strongly modulated in agricultural regions by nutrient inputs (including nitrogen fixation by legumes) and by water inputs through irrigation. Respectively, these inputs remove nutrient and water constraints on plant growth.

Figure 2.15 Mean annual net primary productivity with current climate and agricultural inputs.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

- The six drainage divisions with highest net primary productivity are South East Coast, Tasmania, North East Coast, Murray–Darling Basin, South West Coast and South Australian Gulfs. These correlate with the highest areas of agricultural productivity per unit area and are quite different from the ranking for annual rainfall per unit area (Figure 2.16), which for the top six drainage divisions are Tasmania, Timor Sea, South East Coast, North East Coast, Gulf of Carpentaria and Murray–Darling Basin. These changes in ranking occur because all three modulating factors (in addition to rainfall-saturation deficit, light and agricultural inputs) are exerting significant controls on net primary productivity: the strong influence of saturation deficit means that northern regions (Timor Sea and Gulf of Carpentaria) have a low net primary productivity despite their high annual rainfall. This climatic influence cannot be removed by irrigation or nutrient inputs, and is a fundamental limitation on plant growth in northern Australia. However, from this it should not be interpreted that irrigation potential is limited in these regions.
- Net primary productivity of the urban fringes of Australia's capital cities is high—characterised by intensive horticulture and livestock enterprises.
- Limited light means that Tasmania's net primary productivity is lower than other regions in southern Australia, despite these regions having a lower rainfall.
- Net primary productivity in the southern agricultural drainage divisions (Murray–Darling Basin, South West Coast, South East Coast, South Australian Gulfs) is significantly enhanced by nutrient inputs and irrigation despite their relatively low rainfall.

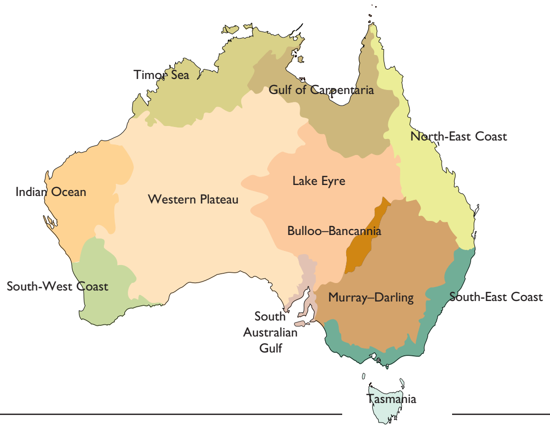
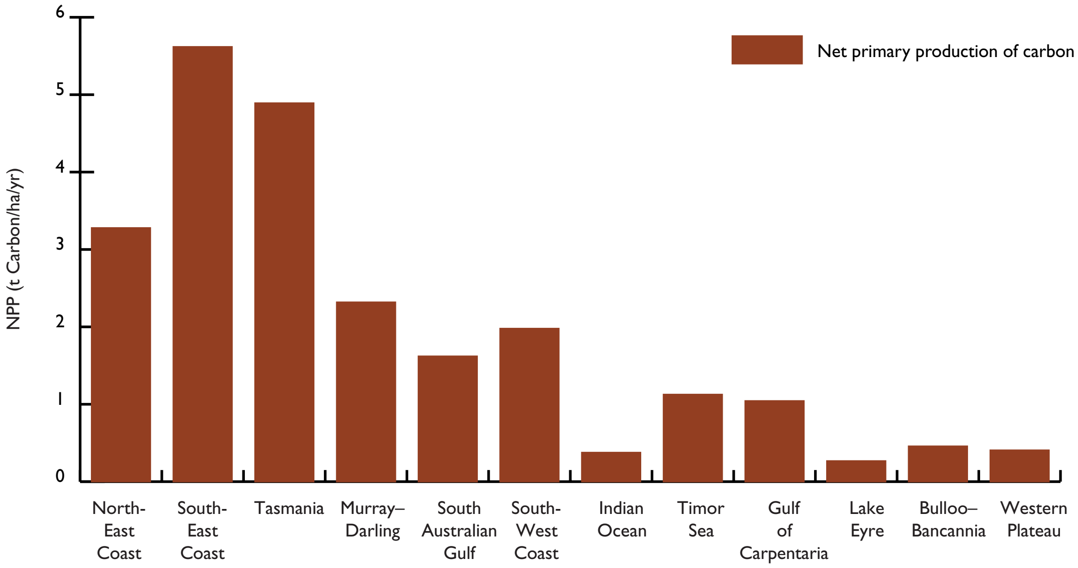
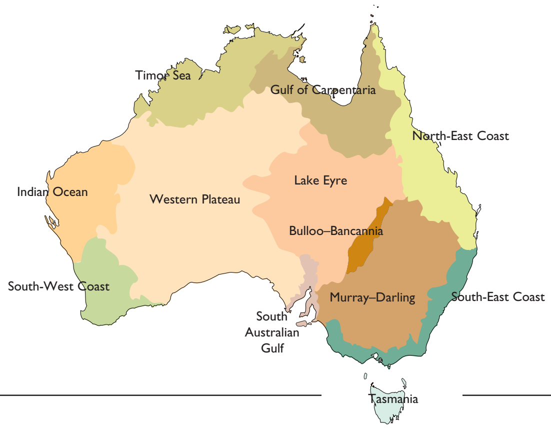


Figure 2.16 Steady-state net primary productivity per unit area, spatially averaged across Australia's drainage divisions again with drainage divisions named.





Carbon stores in biomass and soil

- Carbon stores (figure 2.17) are strongly controlled by net primary productivity (hence also rainfall and saturation deficit), so the distribution for carbon store strongly resemble the distribution for net primary productivity—being higher in southern Australian—the South East Coast, Tasmania, North East Coast, Murray–Darling Basin, South West Coast and South Australian Gulfs drainage divisions.
- The carbon stores are also modulated by temperature because low temperatures slow decay of plant material and high temperatures promote rapid decay.
- The ratio of carbon storage in tropical to temperate regions is lower than the corresponding ratio for net primary productivity, because the tropical carbon stores turn over faster than temperate stores. The coolest parts of Australia (Tasmania and the South East Coast) have a relatively high carbon storage level per unit net primary productivity compared to the warmer tropical regions.

Figure 2.17 Carbon store in biomass (including leaf, wood and roots, that is all above-ground and below-ground biomass), and summed carbon stores in all litter and soil pools.

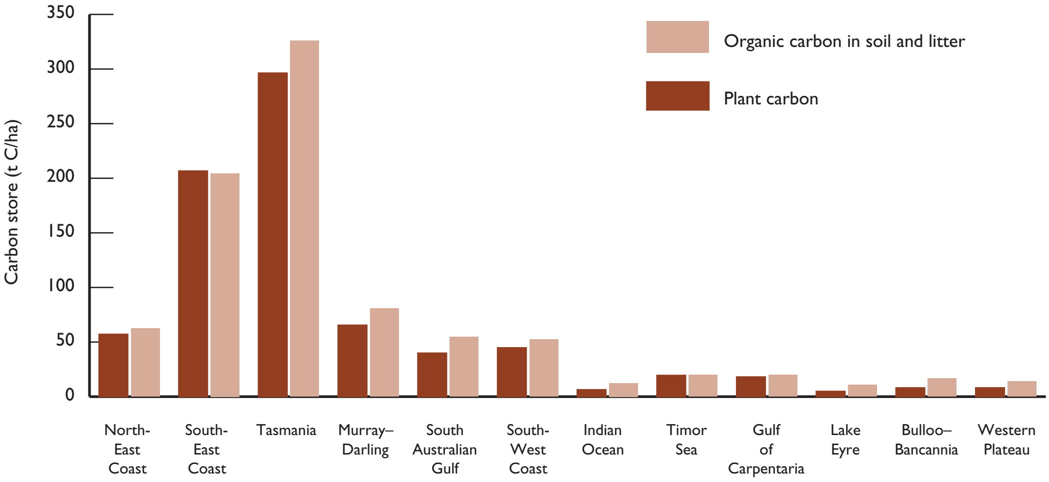
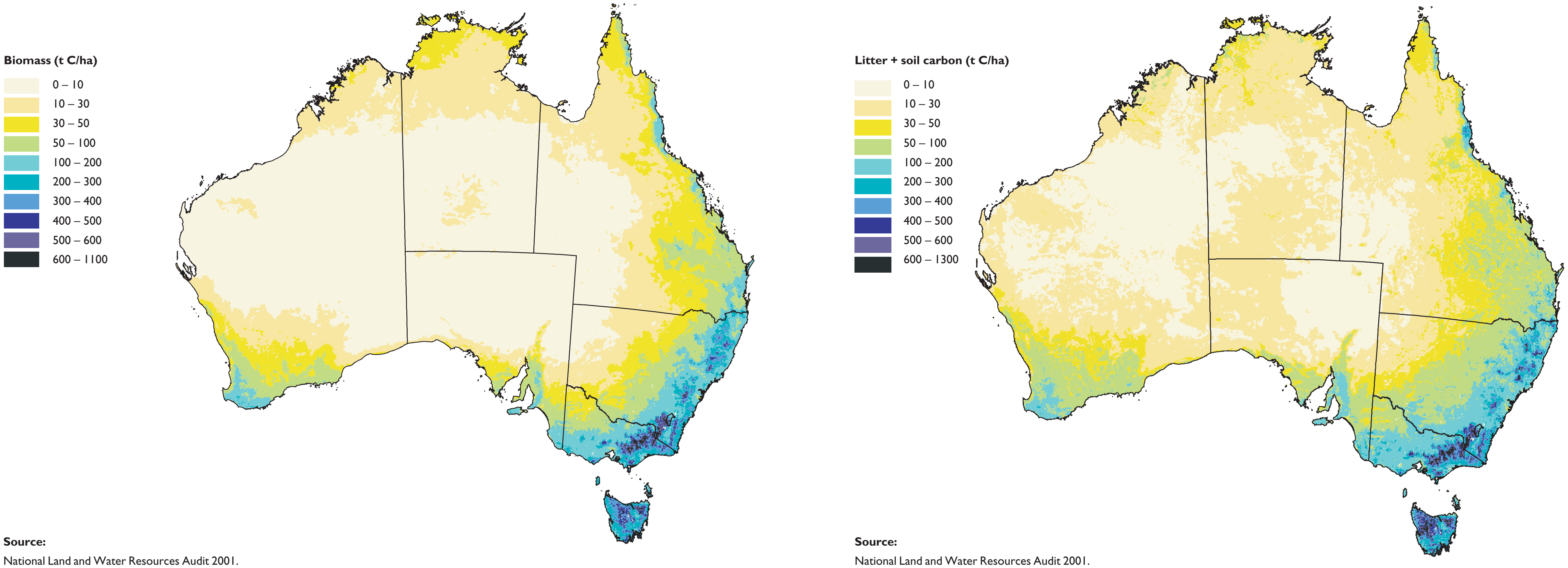


Figure 2.17 Carbon store in biomass (including leaf, wood and roots, that is all above-ground and below-ground biomass), and summed carbon stores in all litter and soil pools.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Changes in the carbon balance brought about by European-style agriculture

- Steady-state net primary productivity and carbon stores were compared under two different external scenarios to understand the extent of change on the carbon cycle as a result of the impact of land management changes associated with the introduction of European-style agriculture since 1788:
    - the first corresponds to present climate and agricultural practices (Figures 2.15, 2.16, 2.17);
    - the second with present climate but with no agriculture (i.e. without water input by irrigation, nitrogen input from sown legumes or fertilisation, phosphorus input from fertilisation, and nitrogen and phosphorus exports off farm in agricultural product).

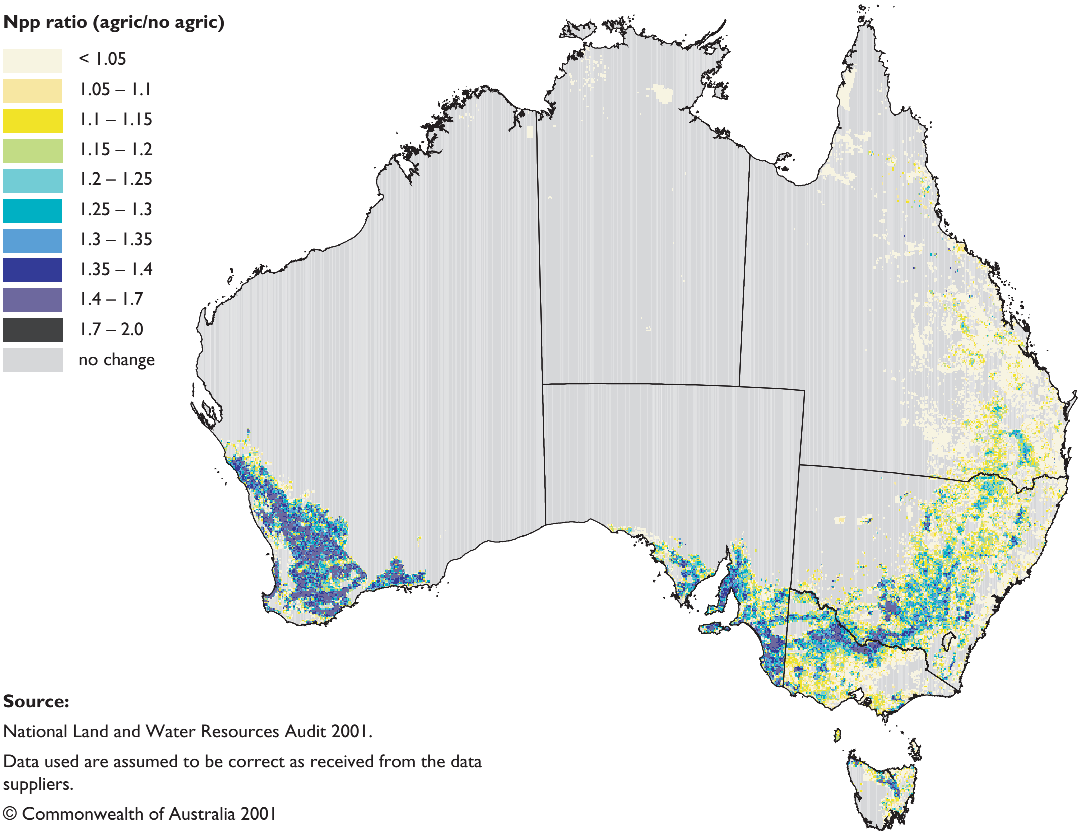
The comparison is between an Australian continent, which is fully equilibrated to current agricultural practices, and a continent that is fully in equilibrium with external forcings in the absence of European-style agriculture, and where climate is assumed to be the same as present climate (Figure 2.18).

Carbon balance (net primary productivity) and Australian agriculture

Water and nutrients have been applied extensively in Australian agriculture.

- Increases in agricultural production will continue to be achieved through nutrient inputs.
- Irrigation and the efficient use of nutrients will continue to contribute to the highest increases in productivity per unit area and returns on agricultural investments. This is explored further from an economic perspective in the Audit's companion report—*Australians and Natural Resource Management 2001*.
- Australian agriculture needs to ensure a balance between farm nutrient input and export is achieved in order to maximise return on investment and to minimise any off-farm impacts. The farm-gate nutrient balance is discussed in detail in the *Nutrient Management* section.

Figure 2.18 Ratio of the steady-state net primary productivity with current agriculture to that without agriculture.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

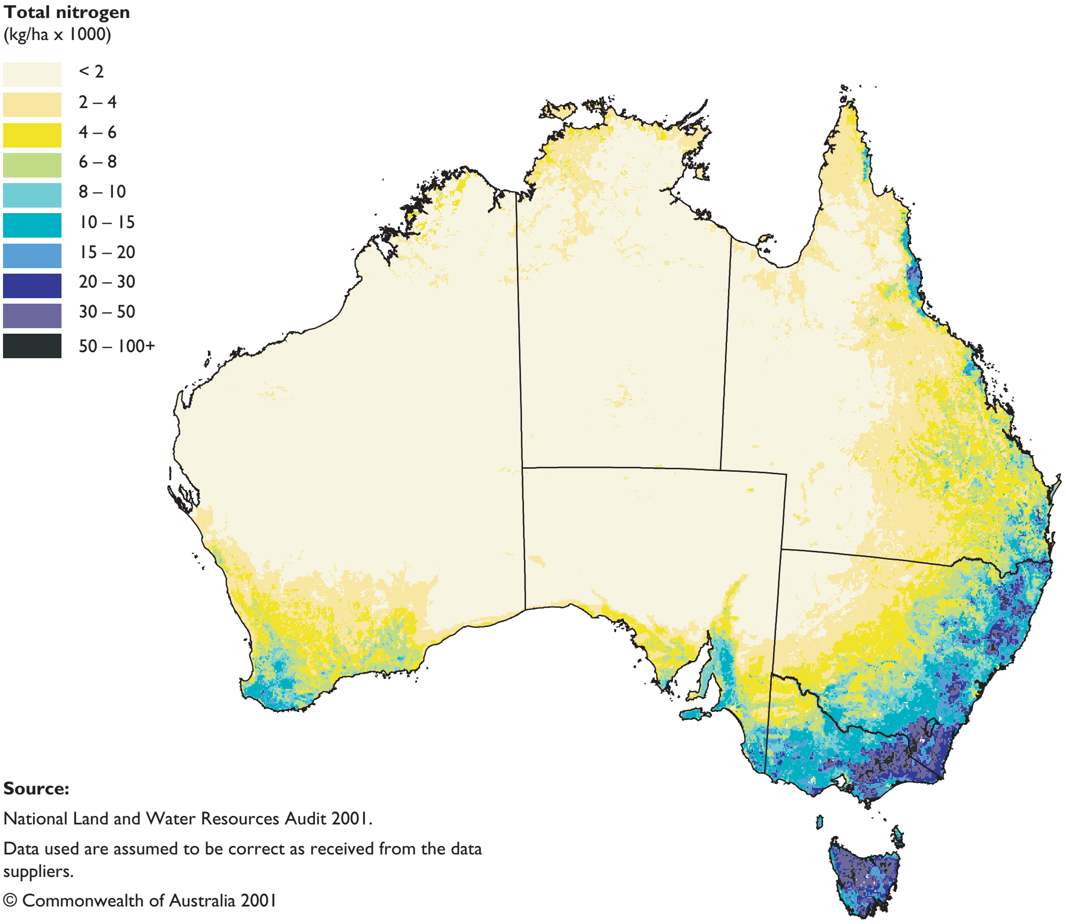
Over the bulk of the continent as shown in Figure 2.18 (the grey region) the ratio (or factor by which net primary productivity has increased) is 1. These are the arid and semi-arid rangelands, where agriculture does not exist. However, in agricultural areas, net primary productivity increased locally (at scale of 5 km cells) by up to a factor of two in response to nitrogen and phosphorus fertilisation and nitrogen input from sown legumes. The ratio is higher in irrigation areas.

The largest increases occurred in the cropping zones of Western Australia, South Australia, Victoria and New South Wales. These increases are relative to natural productivity and thus reflects the role of fertilisers and farming systems in improving soil fertility and thereby increasing production above levels produced naturally.

Plant available nitrogen stores

- Nitrogen stores (Figures 2.19, 2.20) strongly resemble carbon storage and net primary productivity. Nitrogen stores are coupled to carbon through well-defined, but variable nitrogen–carbon ratios in leaves, wood, roots, litter and soil organic matter.
- In the absence of agricultural inputs of nitrogen, saturation deficit and temperature exert similar controls on nitrogen stores as they do on carbon stores.
- Agricultural nitrogen inputs have a relatively higher impact on stores of soil mineral nitrogen than on net primary productivity and the other stores (carbon, organic nitrogen). This has particular implications for rates of soil acidification, and is discussed further in the *Soil Acidification* section of this report.

Figure 2.19 Steady-state store of total plant available nitrogen, consisting of organic nitrogen in litter and soil plus the mineral plant-available nitrogen (including both ammonium and nitrate) under current agricultural practices.

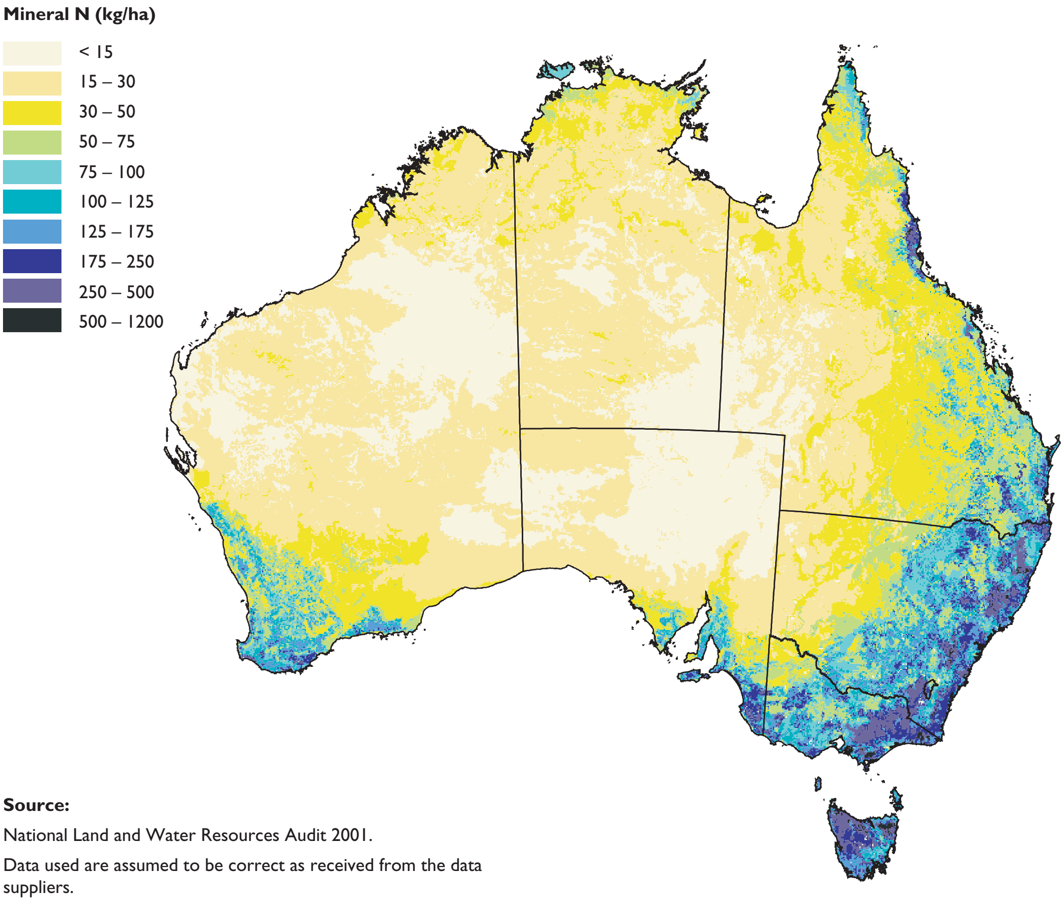


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 2.20 Mineral component of the store of total plant available nitrogen under current agricultural practices.



Source:

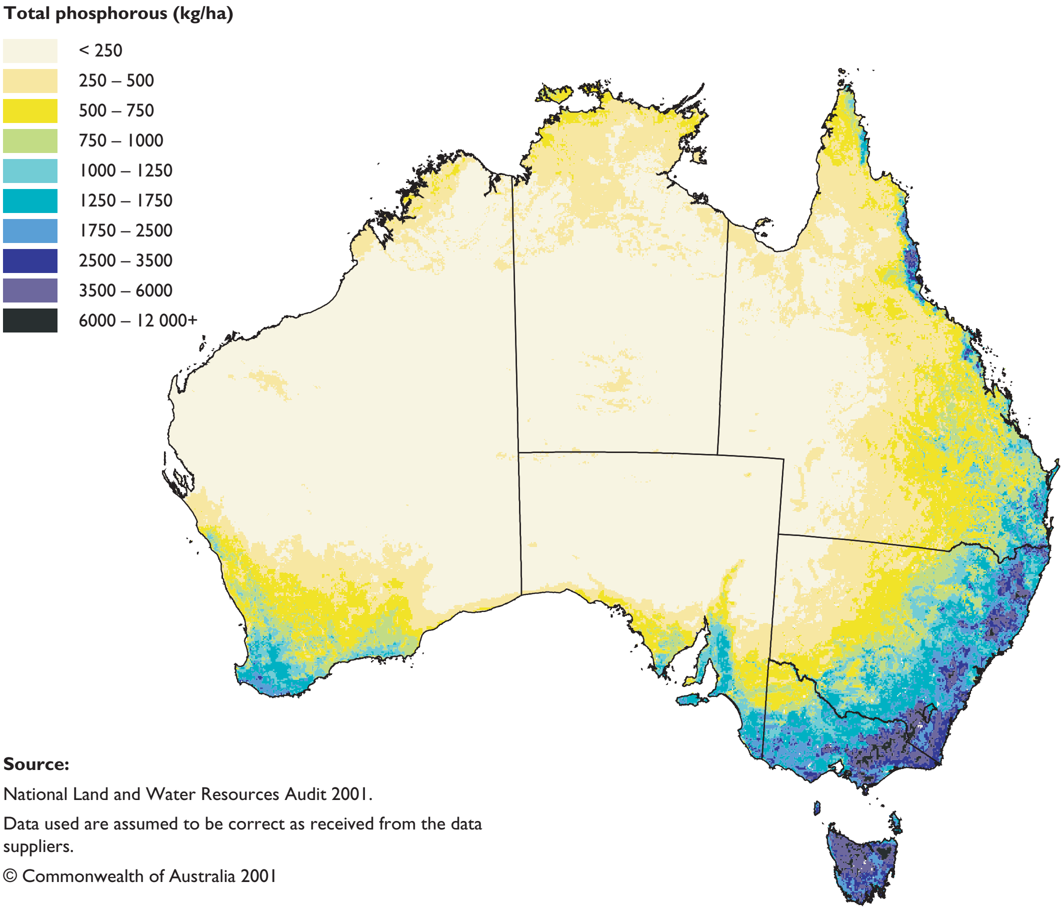
National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Plant-available phosphorus stores

- Phosphorus is present in every living plant and is vital for harvesting the sun's energy for growth and reproduction.
- Phosphorus stores strongly resemble carbon storage and net primary productivity. Phosphorus stores are coupled to carbon through well-defined, but variable phosphorus–carbon ratios in leaves, wood, roots, litter and soil organic matter. Figures 2.21 and 2.22 show phosphorus stores to be higher in south eastern Australia, particularly in the upper catchments of the Great Dividing Range. High levels of phosphorus cycling through the soil and litter pools in northern Australia significantly reduce nutrient build up.
- Total stores of soil phosphorus encompass several pools, the plant-available store being only a small fraction of the total store held within the landscape. (Figure 2.21 and 2.22). Much of the phosphorus is tightly bound to the soil matrix, attached to organic matter or locked up within soil minerals. The availability of phosphorus to plants in these fractions is comparatively low.

Figure 2.21 Steady-state store of total plant-available phosphorus (organic plus labile mineral phosphorus).

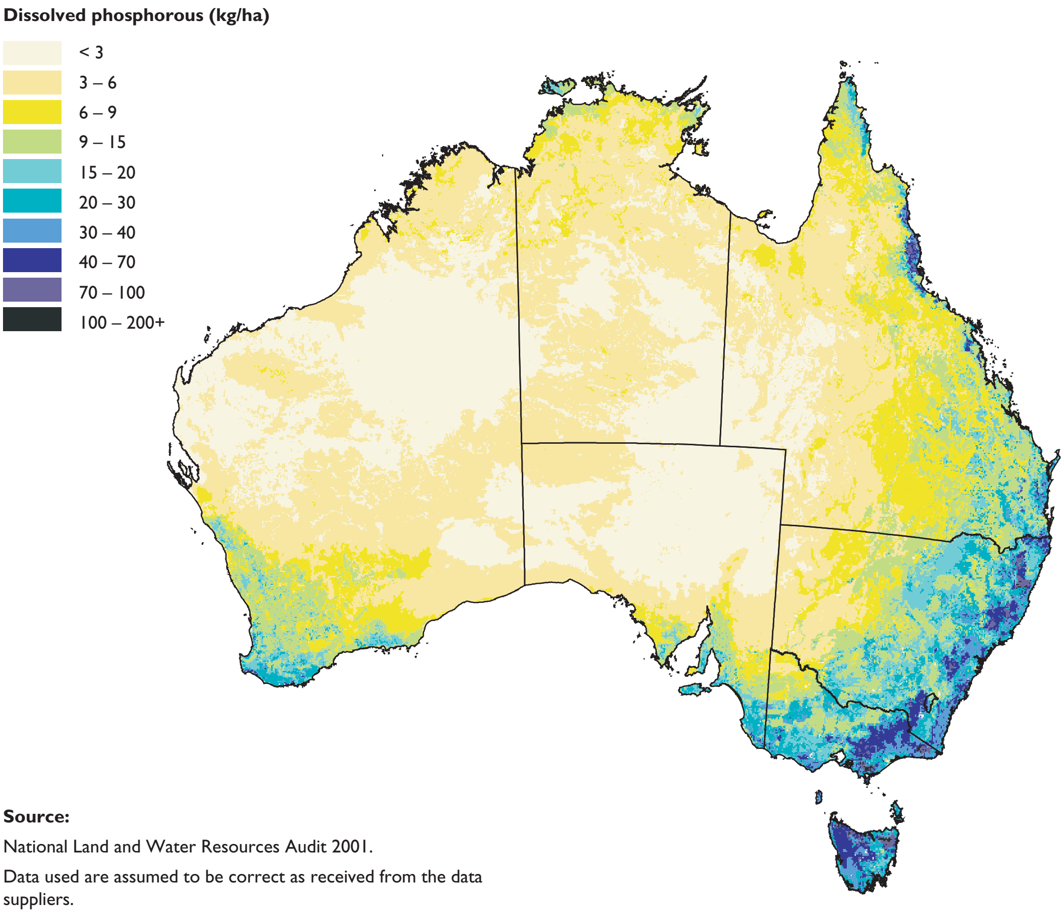


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 2.22 Labile (unstable) mineral phosphorus component of the phosphorus store.



Source:

National Land and Water Resources Audit 2001.

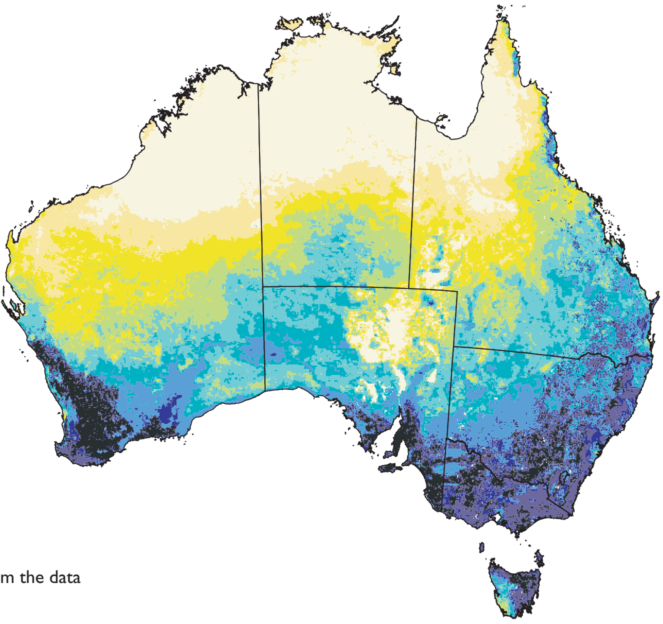
Data used are assumed to be correct as received from the data suppliers.

Dissolved nitrogen and phosphorus concentrations in soil water

Dissolved nutrient concentrations were determined to assess the change in nutrient stores principally as a result of introducing agriculture into the landscape. Dissolved nutrient concentrations were modelled and calculated assuming that the plant available pools of mineral nitrogen and labile phosphorus occur in soil solution. The dissolved nitrogen concentration is the ratio of mineral nitrogen store to soil water store. Dissolved phosphorus concentration is the ratio of the labile phosphorus store to the soil water store.

- Distribution of dissolved nitrogen and phosphorus concentrations are quite different to net primary productivity (Figure 2.15) and carbon, nitrogen and phosphorus stores (Figures 2.16, 2.22, 2.23, 2.24, 2.25) because rainfall has comparable influence on both these stores. Hence, rainfall is not a strong modulator of the nitrogen/phosphorus concentration in soil water. However, a north – south influence on distribution can be seen in Figures 2.23 and 2.24. The higher levels of both nitrogen and phosphorus in solution clearly depict the agricultural regions of southern Australia.
- The effect of saturation deficit (mainly controlled by net primary productivity) on the mineral nitrogen store is greater than the effect of saturation deficit on the soil water store (mainly determined by rainfall or energy limitations). It is predicted that nitrogen concentration in soil water decrease as average saturation deficit increases from temperate to semi-arid tropical environments.
- Modelling also suggests that soil water concentrations of nitrogen and phosphorus may be significant drivers for dissolved nitrogen and phosphorus concentrations in rivers. If so, then climate controls some dissolved riverine concentrations of nitrogen and phosphorus, through saturation deficit, and these riverine concentrations will show a similar south–north gradient to that seen in Figures 2.23 and 2.24. Complicating factors are that:
    - sediment-borne contributions to riverine nitrogen and phosphorus (organic nitrogen, organic phosphorus, sediment-bound phosphorus) will behave differently (see *Water-borne soil erosion* and *Nutrient loads to Australian rivers and estuaries* sections);
    - riverine nitrogen and phosphorus sourced from local pollution (effluent, heavily fertilised crops) will not behave similarly;
    - account needs to be made for processes affecting dissolved nitrogen and phosphorus concentrations in *subsurface* flow from landscapes into rivers (e.g. denitrification in riparian zones leading to loss of nitrogen to the atmosphere, and sorption of dissolved labile phosphorus onto soil particles as secondary or occluded phosphorus that effectively act as a phosphorus sink); and
    - account needs to be made for processes acting on the dissolved nitrogen and phosphorus concentrations in *surface* flow from landscapes to rivers (e.g. water involved in rapid surface run-off is unlikely to equilibrate its nitrogen and phosphorus concentrations with soil water except in a very shallow layer through which surface run-off and soil water are mixed).

Figure 2.23. Modelled dissolved concentrations of nitrogen in soil water (kg N/kg H_2O).

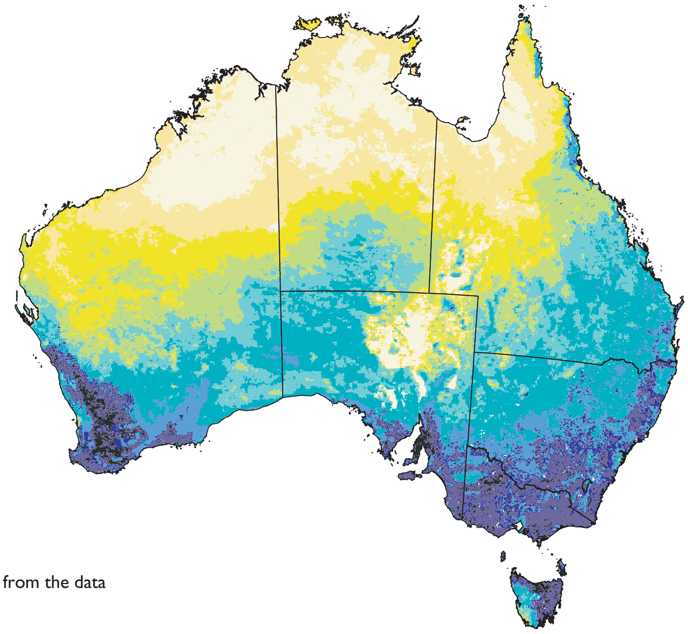


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 2.24 Modelled dissolved concentrations of phosphorus in soil water (kg P/kg H_2O).



Source:

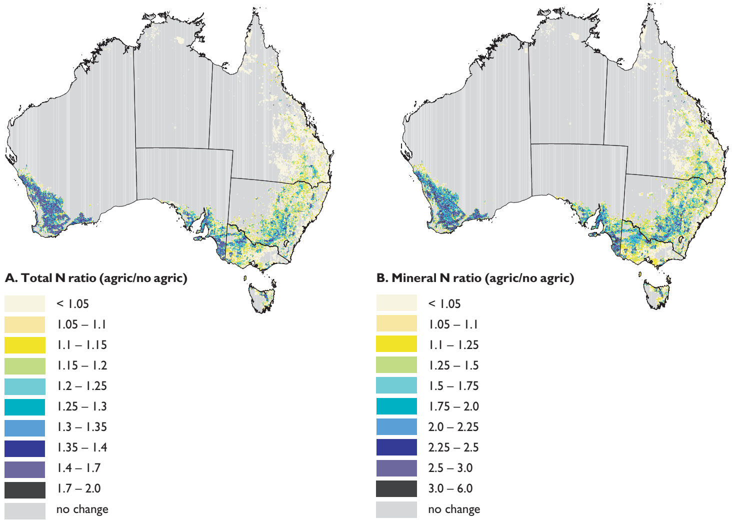
National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Changes in nitrogen and phosphorus stores brought about by European-style agriculture

- Compared to the pre-European settlement era, the advent of agriculture has increased the concentrations of mineral nitrogen, labile phosphorus and the nitrogen and phosphorus concentrations in soil water by a factor of up to 5 (Figures 2.25, 2.26, 2.27). The largest proportional increases were predicted for southern Australian—in particular the south-east region of South Australia and south-west of Western Australia where nutrient levels were naturally low.
- By comparison, agriculture increased plant available nitrogen and phosphorus by up to two times that reached before settlement and show similar regional patterns.

Figure 2.25. Ratio of the steady-state store of total plant available nitrogen (organic plus mineral) with current agriculture to that without agriculture.


A. Total N ratio (agric/no agric)

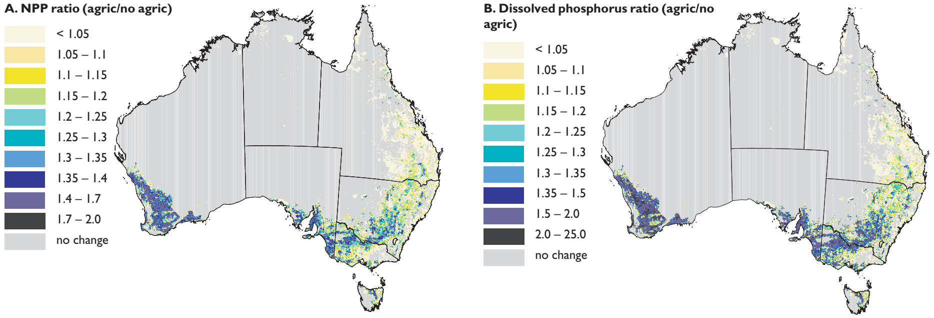
B. Mineral N ratio (agric/no agric)

Source:

National Land and Water Resources Audit 2001.

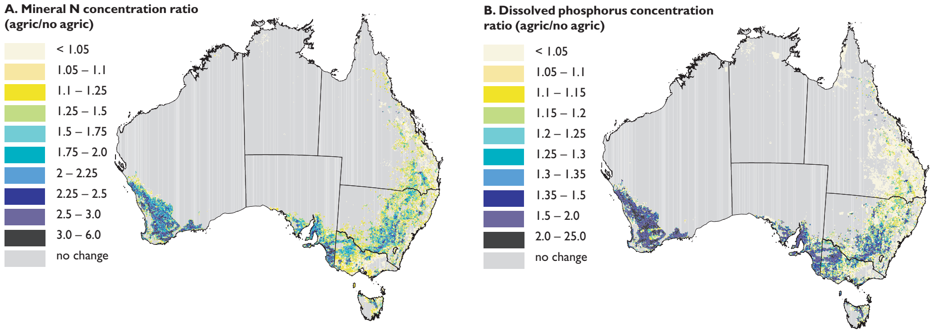
Data used are assumed to be correct as received from the data suppliers.

Figure 2.26 Ratios of mean phosphorus stores with current agricultural inputs (irrigation, nitrogen and phosphorus inputs and offtakes) to mean phosphorus stores without agricultural inputs. **A** is the mean total plant available phosphorus (including organic phosphorus in litter and soil pools and labile phosphorus). **B** is labile phosphorus.


A. NPP ratio (agric/no agric)

B. Dissolved phosphorus ratio (agric/no agric)

Figure 2.27 Ratios of concentrations of mineral nitrogen (**A**) and labile phosphorus (**B**) in soil water with current agricultural inputs to concentrations without inputs.


A. Mineral N concentration ratio (agric/no agric)

B. Dissolved phosphorus concentration ratio (agric/no agric)

Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

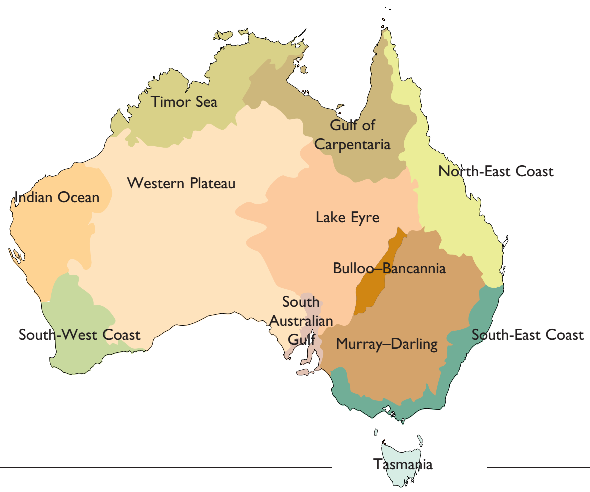
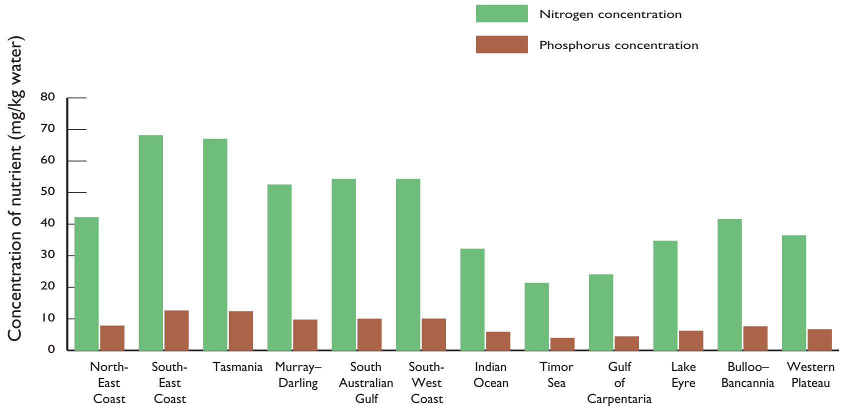
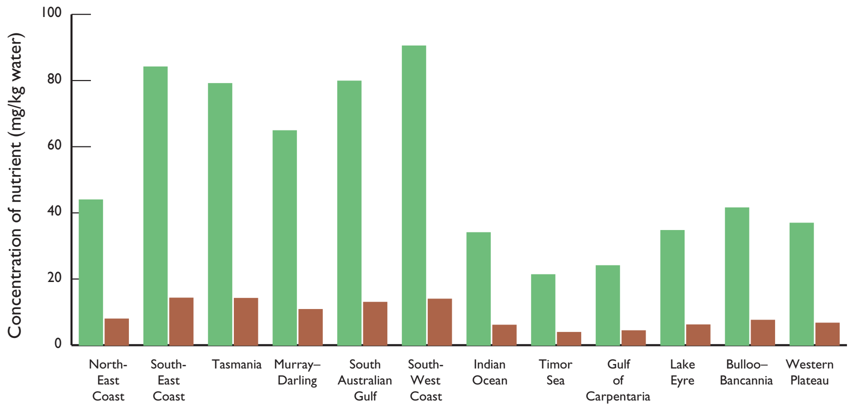


Figure 2.28 Mega-regional view of the response of nitrogen and phosphorus concentrations in soil water to agriculture (concentrations spatially averaged over Australia's 12 drainage divisions), without agriculture (upper) and with current agricultural practices (lower).

Without agriculture



With agriculture



The largest increases in the soil–water nitrogen and phosphorus concentrations occur in the South West Coast, the Murray–Darling Basin and the South Australian Gulfs (Figure 2.28).

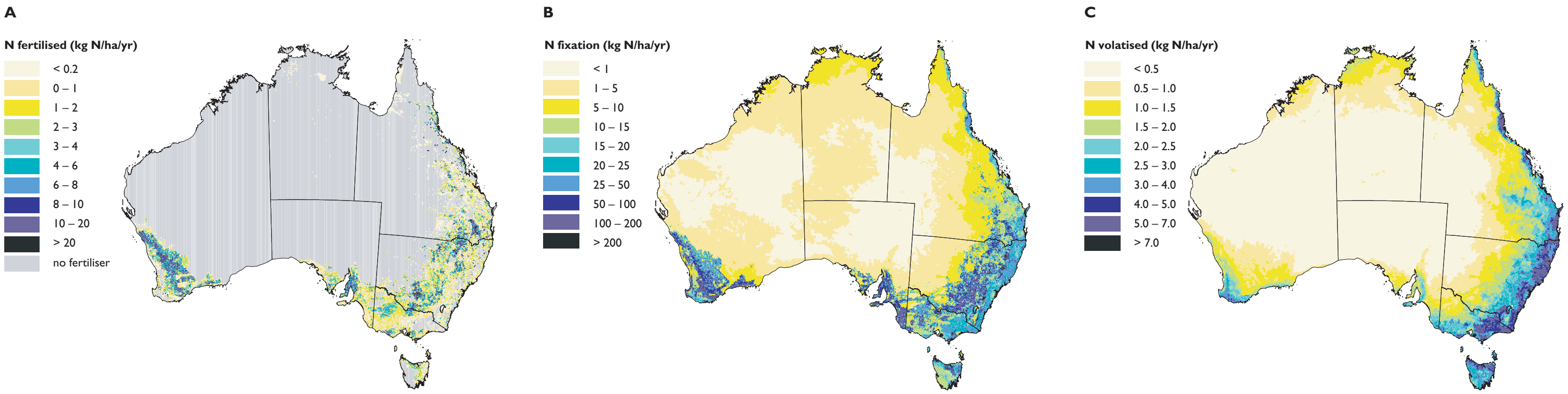
Nitrogen fluxes and total nitrogen balance

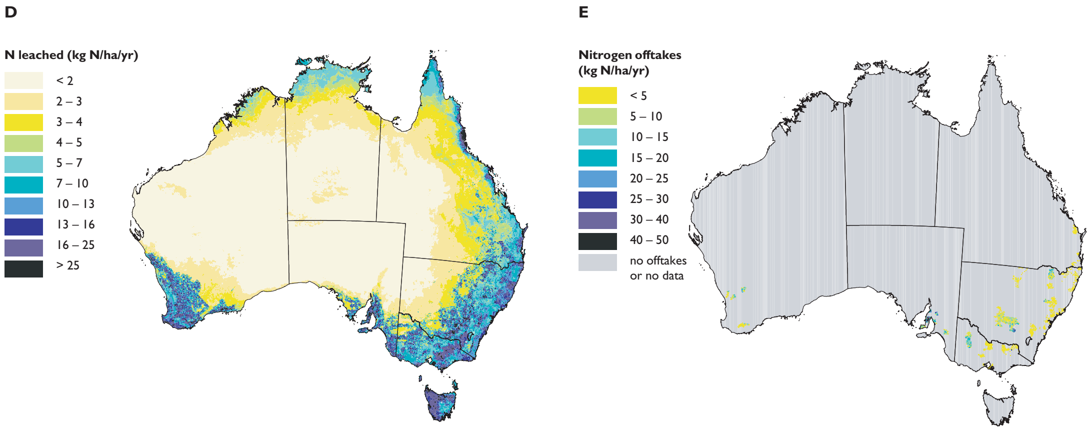
Fluxes contributing to the total landscape store of nitrogen (including nitrogen in plant, litter, soil and mineral pools) for total nitrogen balance are:

- nitrogen input from applied nitrogenous *fertilisers* (Figure 2.29a);
- input from nitrogen fixation by legumes, including native legumes and sown crop and pasture legumes;
- input of nitrogen from the *atmosphere* by *dry* (particulates and gases) and wet *deposition* (rainfall) (Figure 2.29b);
- loss of nitrogen from the landscape to the atmosphere as nitrogenous gases (*volatilisation*), including nitrous oxide and others (Figure 2.29c);
- loss of nitrogen from the plant-available mineral pool by transport in dissolved form (*leaching*), mainly through deep drainage of water (Figure 2.29d);
- horizontal *transport* of nitrogen *in particulate form* by water or wind erosion (operating as either a sink or source depending on whether the net erosion process is depleting or depositing particulate material);
- net removal (*off-farm export*) of nitrogen in *harvested* plant or animal *product*, (can be negative if harvested product from elsewhere is used as an agricultural input, as in use of off-site hay for stock feed) (Figure 2.29e);
- *disturbance* fluxes: fire and grazing. Fire releases nitrogen to the atmosphere as biomass is burned. The effect of grazing (other than that accounted for in animal production exports off farm) is to accelerate loss of nitrogen to the atmosphere as plant nitrogen is excreted by animals.

Most of these (with the exceptions of disturbance and particulate transport) have been estimated explicitly as part of this assessment. The sum of the disturbance and particulate transport fluxes appears as a residual in the closed, steady-state total landscape nitrogen balance, which requires that all the above fluxes sum to zero in the long-term average.

Figure 2.29 Nitrogen fluxes—relative magnitude and large-scale spatial patterns.





Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Summary of nitrogen fluxes

Pre-European settlement:

- Before European-style agriculture was introduced, the nitrogen balance was dominated by input of nitrogen from natural fixation. Contribution from atmospheric nitrogen deposition as an input flux was (and remains) small.
- Pre-agricultural losses of nitrogen occurred through a mixture of volatilisation, leaching and disturbance (grazing and fire). Modelled estimates indicate that leaching caused the largest loss, but substantial uncertainty remains about the magnitudes of each process.
- Spatial distributions of all major nitrogen fluxes prior to European-style agriculture were closely connected with the distribution of net primary productivity.

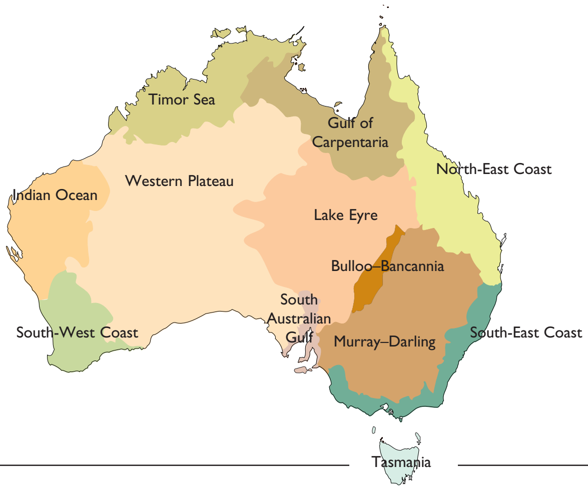
Present day:

- Introduction of European-style agriculture substantially changed the nitrogen budget—on the input side nitrogen fixing remained the largest term, but this has been greatly enhanced in agricultural areas by sown crop and pasture legumes.
- Nitrogen input from fertilisers was a much smaller contributor to continental nitrogen balance though locally significant in areas of high nitrogen-based fertiliser use; nitrogen inputs from sown legumes exceeded those from fertilisers by a factor of seven.
- Losses also occurred through disturbance, leaching and volatilisation in the current nitrogen budget. The magnitude of disturbance has increased dramatically in comparison with the pre-agricultural budget. We attribute this mainly accelerated nitrogen loss to the atmosphere through volatilisation of nitrogen from excreta by grazing stock.
- A significant proportion of the nitrogen being applied agriculturally (either through sown legumes or through fertilisers) is being lost to the atmosphere through a combination of disturbance fluxes and volatilisation.
- Contribution to the national nitrogen budget from nitrogen exported in agricultural produce is small, but regionally important in cropping areas.
- Determination of a continental nitrogen balance is difficult and requires major assumptions (described in detail in project reports on the Australian Natural Resources Atlas).

Phosphorus fluxes and total phosphorus balance

The budget applies to plant available phosphorus, the landscape phosphorus store that interacts directly with the carbon cycle. This includes phosphorus in plant, litter, soil organic matter and the labile mineral pool. As noted previously, plant available phosphorus is only part of the total phosphorus store in the landscape, the remainder being only weakly available for plant growth (secondary phosphorus) or effectively unavailable (occluded phosphorus). The fluxes in the model of landscape balance of plant available phosphorus are:

- input of phosphorus from applied *fertiliser*;
- input of phosphorus from *atmospheric deposition* (mainly through dry particulates);
- loss of phosphorus from inert soil and rock stores by physico-chemical or biological processes (*weathering*);
- loss of phosphorus from the plant-available mineral pool by transport in dissolved form in deep drainage (*leaching*);

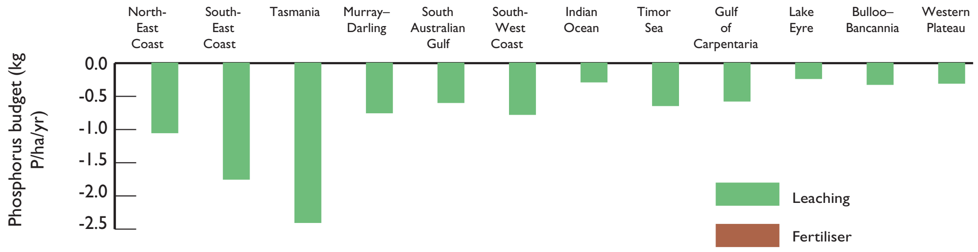


- horizontal *transport* of phosphorus in *particulate* form by water or wind erosion;
- return of phosphorus to an inert soil store (*occluded phosphorus sink*) through the secondary phosphorus pool (the opposite process to weathering);
- net removal of phosphorus *off-farm* in *harvested* plant or animal *product*; and
- the major *disturbance flux* for phosphorus is probably fire, through transport in airborne particulate ash. Phosphorus fluxes due to grazing are likely to involve local recycling on the landscape through plant and soil pools and are unlikely to be major contributors to the overall landscape phosphorus balance.

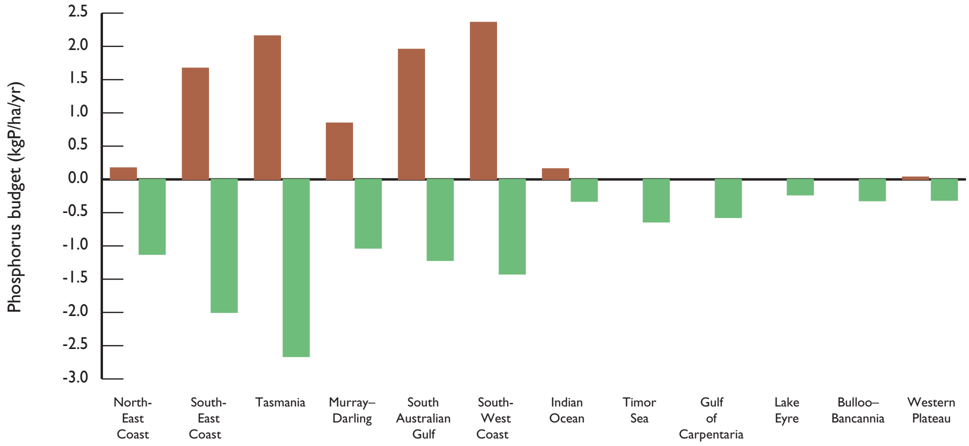
It is not possible to estimate a steady-state landscape balance for plant-available phosphorus. The very slow exchanges within the inert stores of phosphorus in the landscape render the entire balance non-steady even over time scales of millennia. We can only estimate a few of the major fluxes in the balance (Figure 2.30). These estimates suggest that with present agricultural inputs, phosphorus fertilisation is of the same order of magnitude as losses in the agriculturally managed parts of the country.

Figure 2.30 Comparison of flux terms in the steady-state labile phosphorus budget without and with agriculture for the 12 drainage divisions.

Without agriculture



With agriculture



Nutrient balances and Australian agriculture

In developing Australia's agriculture, we have increased landscape nutrient stores much more than we have increased landscape production (net primary productivity). This is especially evident in the 400–700 mm southern agricultural zone. Predicted increases in plant-available mineral nitrogen and phosphorus have been increased by as much as five times (ratio of current to pre-agricultural level), while in the same areas the landscape yield (measured by net primary productivity) has increased by a factor of about two.

On large scales, nutrients are being applied at higher rates than are needed for optimum plant production levels and are approaching, if not well within, diminishing returns. Higher nutrient levels mean that some landscapes are leaking more nutrients into the atmosphere and into soil water and waterways than they were before introduction of European-style agriculture.

Production benefits and the environmental costs from applying nutrients to agricultural land behave quite differently as functions of the nutrient input (Figure 2.31):

- production benefits from nutrient application approach a plateau or a point of diminishing returns as soil nutrient levels become limiting, because plants can only use a finite amount of nutrient before other resources (e.g. water) become limiting.
- environmental costs tend to increase progressively and more steeply as nutrient inputs increase, because damage (e.g. eutrophication in waterways or estuaries) often has a threshold limit. Exceedance of the threshold causes undesirable and usually expensive changes that adversely affect biota and other users of water bodies which may be impossible to reverse.

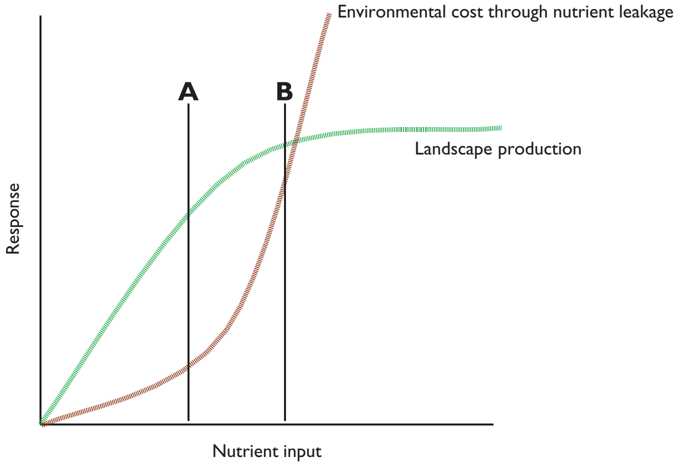
In applying nutrient to landscapes, there is an optimum point (A) at which the net benefit (total benefit minus the cost) is maximised . This point occurs at a nutrient input *below* that required to achieve maximum production. At input rates beyond A, benefits rise progressively more slowly (diminishing returns) while the costs increase at least linearly and probably progressively more steeply.

Production benefits and environmental costs are also usually borne by different groups (benefits accruing on-farm and within farm industries, and costs accruing to users of environmental resources (e.g. drinking water supply, fisheries, environmental amenity).

Overall:

- Australian agriculture is on average beyond the point of most effective nutrient application rates;
- as a priority we need to more closely examine fertiliser and legume regimes to achieve optimum plant productivity—greater precision in use of agricultural nutrients is essential to maintain or reduce costs; and
- attention to on-farm nutrient balance will mean that negative impacts to the Australian environment from agriculture are reduced.

Figure 2.31 Conceptual responses of landscape production and environmental costs to nutrient inputs. **A** is the point of maximum sustainablility with acceptable leakage but less that maximum production, **B** is the point of maximum production at a cost of high leakage and ecological damage.



REFERENCES AND FURTHER READING

AWRC 1987, 1985 *Review of Australia's Water Resources and Water Use*, Australian Water Resources Council/Department of Primary Industries and Energy, Australian Government Publishing Service, Canberra.

Barrett D.J. 2001, *NPP multi-biome: VAST calibration data, 1965-1998,* available on-line [http://www.daac.ornl.gov/] from Oak Ridge National Laboratory Distributed Active Archive Center, USA

Gifford R.M., Cheney N.P., Noble J.C., Russell J.S., Wellington A.B. & Zammit C. 1992, 'Australian land use, primary production of vegetation and carbon pool in relation to atmospheric carbon dioxide concentration', in *Australia's Renewable Resources: Sustainability and Global Change. BRR Proceedings No. 14.* R.M. Gifford & M.M. Barson (eds), Bureau of Rural Resources and CSIRO Division of Plant Industry, Canberra, Australia.

IPCC 2001, 'Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change', J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell & C.A. Johnson (eds), Cambridge University Press, Cambridge.

Landsberg J.J. & Waring R.H. 1997, 'A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning', *Forest Ecology and Management,* vol. 95, pp. 209–228

Lu H., Raupach M.R. & McVicar T.R. 2001, *Decomposition of vegetation cover into woody and herbaceous components using AVHRR NDVI time series,* CSIRO Technical Report 35/01, CSIRO Land and Water, Australia.

McKenzie N.J., Jacquier D.W., Ashton L.J., & Cresswell H.P. 2000, *Estimation of soil properties using the Atlas of Australian Soils,* Technical Report 11/00, CSIRO Land and Water, Australia.

Parton W.J., Schimel D.S., Cole C.V. & Ojima D.S. 1987, 'Analysis of factors controlling soil organic matter levels in Great Plains grasslands', *Soil Science Society of America Journal* vol. 51, pp. 1173–1179.

Parton W.J., Scurlock J.M.O., Ojima D.S., Gilmanov T.G., Scholes R.J., Schimel D.S., Kirchner T., Menaut J.C., Seastedt T., Moya E.G., Kamnalrut A. & Kinyamario J.I. 1993, 'Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide', *Global Biogeochem. Cycles* 7, pp. 785–809.

Parton W.J., Stewart J.W.B. & Cole C.V. 1988, 'Dynamics of C, N, P and S in grassland soils: a model', *Biogeochemistry* vol. 5, pp. 109–131.

Prosser I.P., Rustomji P., Young W.J., Moran C.J. & Hughes A.O. 2001, *Constructing River Basin Sediment Budgets for the National Land and Water Resources Audit*, CSIRO Land and Water Technical Report 15/01, CSIRO Land and Water, Canberra.

Raupach M.R., Barrett D.J., Briggs P.R. & Kirby J.M. 2001, 'Terrestrial biosphere models and forest-atmosphere interactions', in R. Vertessy & H. Elsenbeer (eds), *Forests and Water*, IUFRO, (in press).

Raupach M.R., Kirby J.M., Barrett D.J. & Briggs P.R. 2001, *Balances of water, carbon, nitrogen and phosphorus in Australian landscapes: (1) Project description and results,* CSIRO Land and Water Technical Report (in press).

Raupach M.R., Kirby J.M., Barrett D.J. & Briggs P.R. 2001, *Balances of water, carbon, nitrogen and phosphorus in Australian landscapes: (2) Model formulation and testing,* CSIRO Land and Water Technical Report (in press).

Young W.J., Prosser I.P. & Hughes A.O. 2001, *Modelling Nutrient Loads in Large-Scale River Networks for the National Land and Water Resources Audit,* CSIRO Land and WaterTechnical Report (in press).

SUMMARY

Soil fertility

- The phosphorus, sulfur and calcium status of Australia's agricultural soils have been increased from their inherently infertile state, by application of fertilisers and soil ameliorants. Areas of low to marginal phosphorus status still exist in many regions.
- Australia's topsoils are generally well endowed with potassium, calcium and magnesium, but potential deficiencies exists in some regions

Farm gate nutrient balance

- Balances for nitrogen, phosphorus, sulfur and calcium varied from neutral (inputs = exports) through to positive (inputs > exports) in many regions, suggesting that supply is now approaching near-optimal levels, and soil nutrient reserves are not being mined.
- Potassium and magnesium balances were negative (inputs < exports) in most regions, but most Australian soils have good reserves, or potassium fertilisers are being applied where there are deficiencies.
- Negative balances, signifying soil nutrient depletion, existed in major regions of Queensland (all nutrients); the Victorian Wimmera (nitrogen, phosphorus and potassium); and parts of northern New South Wales and the Riverina (phosphorus). To gain a more precise spatial understanding of these findings, further regional scale investigations would be required.
- Highly positive balances often existed in regions where dairying and horticulture co-exist, suggesting improvements in the efficiency of nutrient use are required.

SUMMARY

Nutrient management

- Australian agriculture has moved to managing nutrients on a site-specific basis.
- Soil testing increased sharply during the 1990s.
- Nitrogen fixation by pasture and grain legumes continues to be a major supplier of nitrogen to soil—especially in southern Australia.
- Nitrogenous fertiliser use has increased 2.5 times over the last 10 years, with most going on to crops. This has boosted production, but may also increase risks of **groundwater pollution** on lighter soils and **soil acidification**.
- In cropping areas, phosphorus fertilisers are now directed to crops, with pastures relying on residual soil phosphorus.
- Regional industry case studies on nutrient use revealed the importance of identifying regions most at risk to depletion and off-site losses of nutrients.
- Adoption of conservation practices (e.g. minimum tillage, stubble retention, green cane harvesting) promote improvements to the physical, chemical and biological condition of agricultural soils.

INTRODUCTION

Most Australian soils are naturally infertile and need extra nutrients to maximise agricultural yields. During Australia's agricultural history, the level of nutrients that most limit yield potential have been progressively built up. After reaching optimum levels, annual inputs are adjusted to meet losses through soil processes (e.g. leaching or immobilisation) and through export of harvested products via the farm gate. Nutrient inputs have also increased as prospective yields have increased. This is attributable to factors such as improved varieties; rotations; fallow moisture retention; irrigation; and better weed, disease and pest control. Additions to the soil include fertilisers (supplying adequate amounts of essential plant nutrients), soil ameliorants (e.g. lime, dolomite and gypsum that chemically and physically improve the soil) and the use of legumes to increase soil nitrogen status.

The introduction of commercial soil and plant testing during the 1970s enabled nutrient management decisions to move from broad district guidelines towards site-specific management.

A knowledge of nutrient balance (i.e. whether inputs are less than or greater than exports) in regional farming systems and assessments of current nutrient status of agricultural soils is useful to help maintain and optimise productivity while remaining benign to the environment (Magdof et al. 1997, SCARM 1998).

These nutrient management decisions are especially important for higher input, intensive systems of land use.

The context for the movement and use of nutrients at a landscape scale has been outlined in the *Landscape balances* section. This section focuses on nutrient management on farm—specifically fertiliser use and nutrient offtakes harvested in produce. Nutrient status reported here relates to agricultural land use not native ecosystems. It should be noted that nutrient requirements vary significantly between agricultural land uses.

Water quality

Nutrients from diffuse and point sources enrich regional water bodies and coastal estuaries increase the risk of algal blooms and lower water quality. Nitrate contamination of ground waters can occur through leaching, especially on sandier soils (Dillon 1988, Anderson et al. 1998, Pakrou & Dillon 2001). This can affect the quality of domestic and stock water. These processes may pose future problems for rural communities.

Soil acidification

Nitrogenous fertiliser use has more than doubled in the past decade (ABARE 2000). Increased use of ammonium-based nitrogenous fertilisers can accelerate soil acidification (see *Soil acidification* section). Plants grown on severely acidic soils have stunted root systems, lowering their uptake of water (and hence yield) and increasing the amount of water moving deeper into the soil profile, or laterally down slope (e.g. Ridley et al. 2001). Acidic soils may also contribute to greater soil erosion through decreased ground cover.

Animal health

Nutritional imbalances of livestock pasture and fodder can induce disorders (e.g. hypomagnesaemia), which seriously impact on productivity.

SUMMARY OF METHODS

Soil fertility

The Audit's Australian Soil Testing Inventory was developed through acquiring and merging soil testing data sets from 12 private and public sector agencies operating commercial services for farmer clients. The data cover the years 1990 to 1999 (eastern Australia) and 1989 to 1998 (Western Australia) and were dominated by samples of surface soils (0–10 cm and 0–15 cm depths of sampling). About 640 000 samples were collated—58% of the samples originated from Western Australian services.

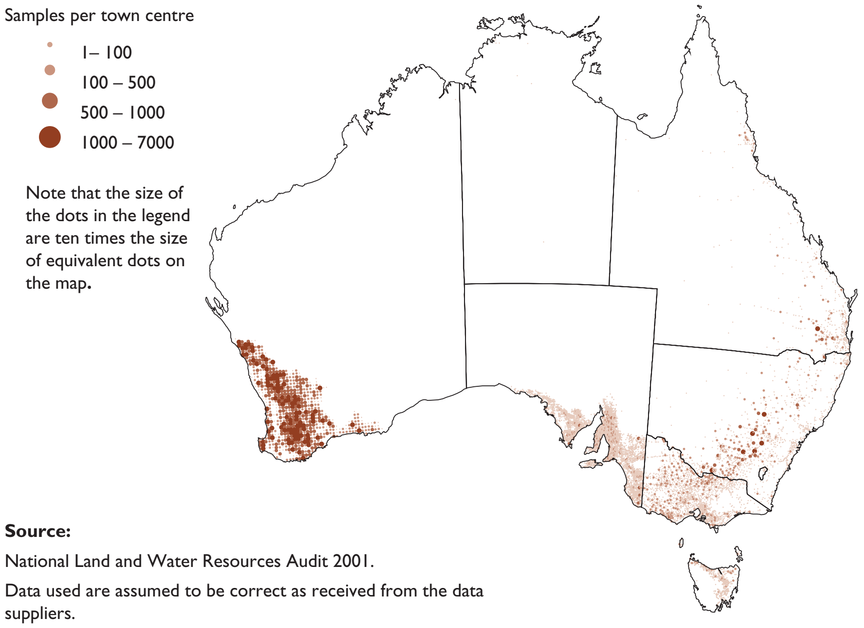
Assessed soil properties included: soil pH_{Ca}, organic carbon, extractable soil phosphorus, potassium and sulfur, and exchangeable calcium and magnesium. Soil nitrate (0–60 cm depth of sampling) and exchangeable calcium and magnesium could only assessed for eastern Australian soils.

The samples were neither randomly collected nor were they derived by stratified sampling. They were geo-referenced to map points—either nearest township (mostly in eastern Australia), cadastral centroids (~50% of South Australian samples), 20 km grid centres (Western Australia) and to accurate map grid coordinates (some data from the Murray Irrigation Area and Tasmania).

Summary statistics for all soil tests—including mean, minimum, maximum, median, standard deviation and rudimental skewness test—were prepared for each township location. Interpolated maps for each soil property were generated as triangular irregular networks for mean soil test values of the geo-referenced map points *to provide broad spatial perspective of soil nutrient status in agricultural regions of Australia.* The mapping approach assumed that map point mean values were representative of the surrounding region. This is more likely where map points are spaced closely, but more tenuous in regions where sampling points are more sparse—in these situations a threshold of approximately 1960 km^2 was selected as a cut-off and remaining town locations are shown as points with a standard radius of 25 km. An example of the point distribution and sample density is shown in Figure 3.1.

Decision rules for classifying and mapping soil fertility status were based largely on the Australian Soil Test Interpretation Manual (Peverill et al. 1999). The area in each nutrient class was estimated for each State, with non-agricultural areas being excluded. Reliability will depend on the spatial accuracy of the interpolated maps generated for each soil property.

Figure 3.1. Point and sample density of townships for soil organic carbon—an example.



Note that the size of the dots in the legend are ten times the size of equivalent dots on the map.

Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Regional farm-gate nutrient balance

Spatial and temporal trends for annual 'farm-gate' nutrient balance were estimated for agricultural regions. Data for calculating nutrient balance were aggregated to statistical local areas for the years 1992/93 to 1996/97 in eastern Australia and from 1989/90 to 1996/97 for Western Australia. Nutrient balances were derived for nitrogen, phosphorus, potassium, sulfur, calcium and magnesium.

Components for farm-gate nutrient balance are:

- nutrient inputs; and
- nutrient exports in harvested farm products.

Farm gate nutrient balance for a given statistical local area is the difference between total inputs and total exports (nutrient inputs minus nutrient exports). Balance was calculated as *kilograms of nutrient per hectare* and mapped to illustrate spatial and temporal trends. Data sets were assembled to derive nutrient balance (Figure 3.2).

Variables on the nutrient input side were:

- nutrients purchased as fertilisers;
- soil conditioners (lime, dolomite and gypsum);
- nitrogen fixed by pastures and grain legumes; and
- nutrients associated with the net movement of fodder across statistical local area boundaries.

Regional data for nutrient from rainfall or irrigation water were unreliable and not used. Nutrient exported in farm products were calculated using the volume of harvested produce and nutrient concentrations in each commodity. Exports included the net transfer of nutrient in livestock across statistical local area boundaries.

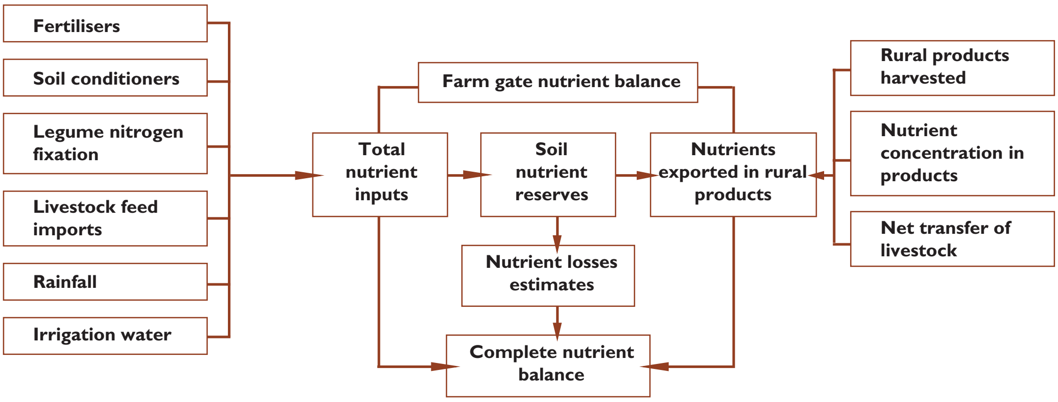
Farm-gate nutrient balances can be positive (inputs > exports), negative (inputs < exports) or neutral (negligible difference). A neutral balance is considered a sustainable target, providing nutrient losses are minimal. No account was taken of nutrient recycling (especially important in grazing systems), soil nutrient immobilisation or off-site losses of nutrients for estimates of farm-gate nutrient balance.

Losses of nitrogen and phosphorus (expressed as kg/ha) to regional water bodies are typically small compared with those accounted for within the farm-gate balance equations, but the total loads of nutrients exported (tonnes per year) within catchments may be considerable (see *Nutrient loads to Australian rivers and estuaries* section). Industry case studies on partial nutrient balance confirm that appreciable nutrient losses are possible in different farming systems.

Interpretation: a consistent negative balance for a specific nutrient indicates that farming systems are progressively depleting soil nutrient reserves, but this does not always infer that these soils will respond to nutrient additions. Rather it may indicate that the soils have a good level of natural fertility, that exceeds the amount of nutrient removed annually in harvested products.

In contrast, a highly positive nutrient balance infers that nutrient efficiencies might be achieved by reducing levels of nutrient addition, that in turn may limit off-site nutrient losses.

Figure 3.2. Nutrient pathways in farming systems.



Soil testing

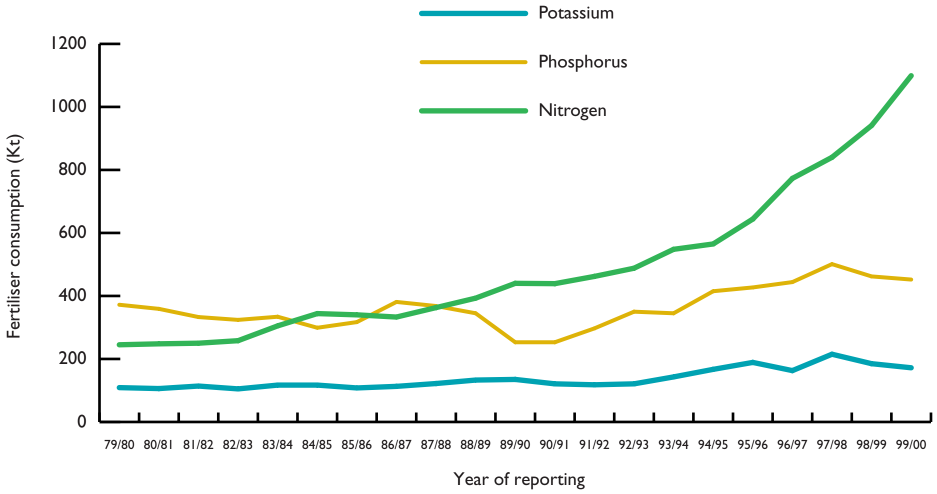
The use of soil testing by farmers increased markedly during the 1990s, especially in eastern Australia. Soil testing in Western Australia remained high and steady during the same period. Currently, about 106 000 samples are analysed annually, which equates to about 1 sample/1000 ha in the agricultural zone. This is a most positive signal, indicating that farmers are increasingly using soil testing as an aid for making better nutrient management decisions.

Fertiliser use (nutrient input)

Consumption of nitrogen, phosphorus and potassium fertilisers in Australia have increased in recent years—growth in nitrogen use accelerated more than two and a half times during the 1990s (ABARE 2000). Use of nitrogenous fertilisers now greatly exceeds phosphorus consumption (Figure 3.3). The reasons for this upsurge in nitrogen use is associated with:

- deterioration in legume content of some pastures (Hamblin & Kyneur 1993);
- a growing awareness and promotion that rates of organic nitrogen mineralisation in agricultural soils were not meeting nitrogen demands of intensively cropped rotations or zero tilled soils (Knopke et al. 2000, Angus 2001);
- increased plantings of nitrogen-fertilised canola crops (Angus 2001);
- improved crop rotations and recognition of the benefit break-crops (e.g. canola) provide in cereal rotations for controlling root diseases and nematodes;
- adoption of shorter-stemmed, higher yielding cereal varieties, less prone to lodging and 'haying off';
- introduction of high analysis ammonium phosphate fertilisers from the 1970s and 1980s to cropping regions of southern Australia (replacing traditional superphosphate applications) and increased use of urea in cropping regions; and
- declining protein levels in wheat (identified and widely promoted in 1989), and the introduction of premium prices for higher protein grades of wheat.

Figure 3.3. Trends in NPK fertiliser consumption in Australia (1979–1999).



Factors affecting fertiliser decisions

Land use and climate have major influence on fertiliser use decisions confirming that:

- trends in the levels of use of fertilisers were consistently lower in more arid, low yielding environments of the cropping zone than in more reliable, higher yielding regions (see Figures 3.4 and 3.15)—decisions on fertiliser use match anticipated returns.
- adverse seasonal conditions experienced in the drought year, 1994, markedly depressed fertiliser use generally during this year *and* the next year—especially noticeable across dryland cropping regions (see Figure 3.4 for phosphorus).
- sugar cane and horticultural production systems used substantially higher levels of fertiliser nutrients (kg nutrient/ha) than dryland crop and pasture systems. Phosphorus use in dryland cropping areas is directed to the cropping phase. However, fertiliser use on dairy pastures (which are mostly in high rainfall areas or are irrigated) has been increasing—Fertilizer Industry Federation of Australia estimates that 48% of the total value of fertilisers applied to pastures in Australia are now applied on dairy farms.

Figure 3.4 Annual phosphorus fertiliser applications rates (kg P/ha) for crops (1992–1996).

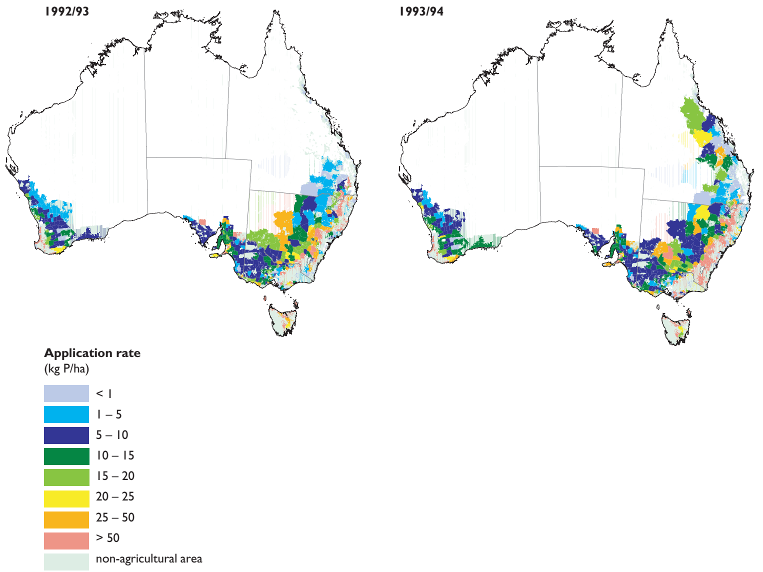
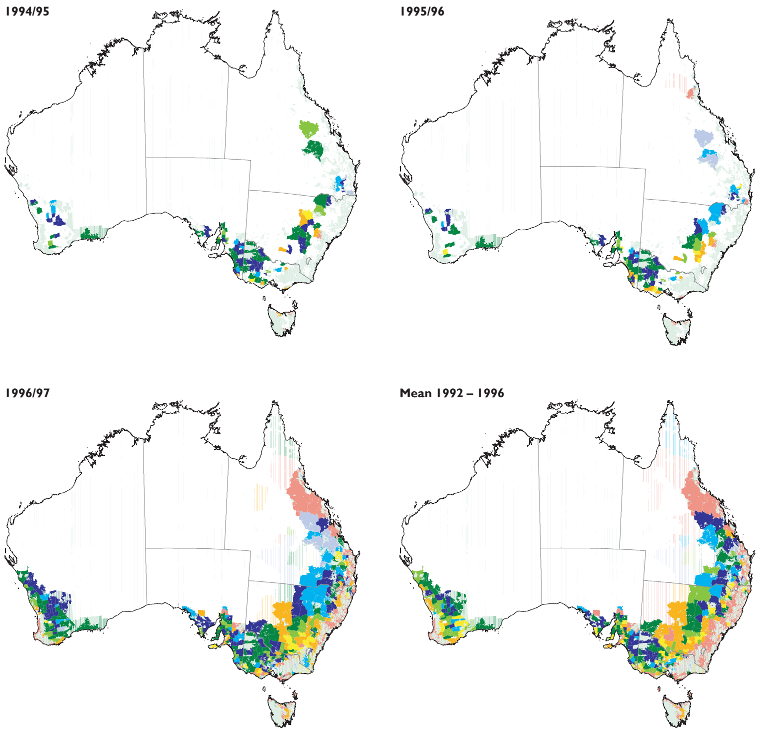


Figure 3. 4. Annual phosphorus fertiliser applications rates (kg P/ha) for crops (1992–1996).



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Other sources of nutrient

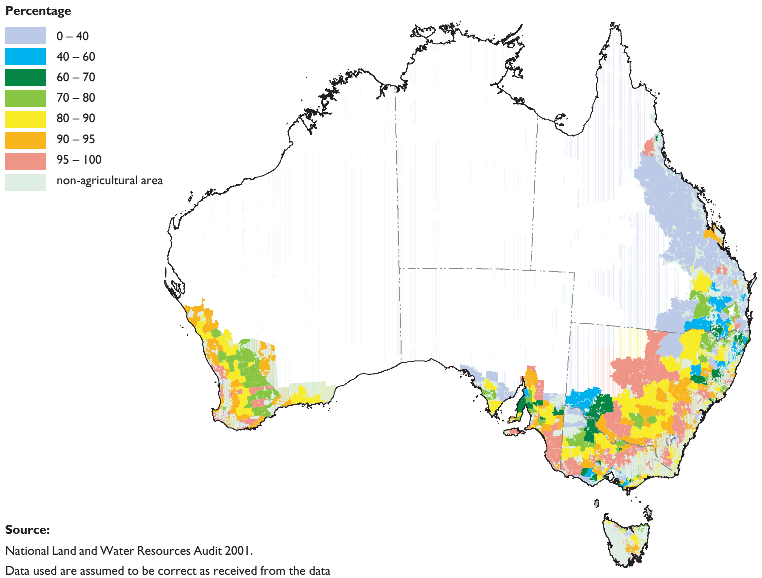
Legume nitrogen fixation—a major contributor to nitrogen supply

Most southern Australian farming systems still rely substantially on nitrogen fixation by legumes to replenish soil reserves after cropping cycles and to provide quality livestock feed. Where legumes were grown, the average addition of nitrogen through atmospheric fixation was estimated to vary from <5 to >300 kg N/ha/year, with areas >100 kg N/ha being common. In southern Australian regions nitrogen fixation contributed over 60% of the total input of nitrogen (Figure 3.5).

In tropical and sub tropical regions, addition of nitrogen from legumes was mainly contributed through grain legume crops and was correspondingly lower than for southern Australia.

Organic matter needs to be decomposed by soil biota to release nitrogen for use by plants. This means that in the more reliable and productive cropping regions, demand may exceed supply resulting in a greater reliance on fertiliser.

Figure 3.5 Contribution of nitrogen fixation to total nitrogen supply (averaged 1992–1996).



Source:

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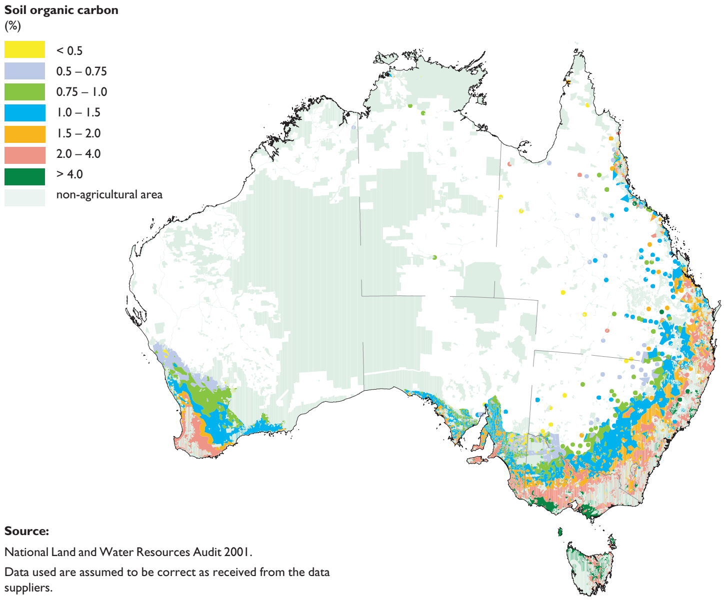
Soil organic matter

Soil organic matter contributes to the retention and cycling of soil nutrients. Organic carbon reserves (reflecting soil organic matter content) are mainly determined by regional climatic conditions: as rainfall decreases and/or temperature increases, soil organic matter levels decrease, since these climatic factors largely determine inputs and decomposition levels. Nationally, 25% of the land had organic carbon values less than 1% and 25% had values exceeding 2% (Figure 3.6, Table 3.1).

Land management practices can modify soil reserves of organic matter: the reserves are lower in cropping zones (greater soil disturbance) than under permanent pastures and are higher in irrigated soils. Very low levels exist in the drier Mallee soils of southern Australia, where conservation farming practices should continue to be promoted.

Management options for improving soil organic matter status include stubble retention, minimum tillage, green trash blanketing and applications of mill mud (sugar cane), green manuring, growing pastures and maximising water use efficiency (Uren 1991).

Figure 3.6 Distribution of topsoil organic carbon determined by commercial soil testing (1989–1999).



Source:

National Land and Water Resources Audit 2001.

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Table 3.1 Areas of agricultural land (km^2)* in each State** assessed having specified soil organic carbon (%) ranges.

State	< 0.5%	0.5–0.75%	0.75–1.0%	1–1.5%	1.5–2%	2–4%	> 4%	Total area
Queensland	2	1 883	3 289	44 495	34 045	21 337	657	10 5708
New South Wales	531	12 310	32 943	122 735	64 432	54 054	4 914	281 920
Victoria	1 210	12 255	15 504	19 255	20 394	56 243	16 654	141 516
Tasmania	0	0	1	3	55	8 161	8 977	17 197
South Australia	4 102	14 773	23 599	44 139	19 693	16 481	1 371	124 157
Western Australia (sw)	922	36 351	54 738	61 079	15 764	27 858	4	196 716
Northern Territory	0	0	30	359	83	0	0	472
National	**6 767**	**77 572**	**130 104**	**282 065**	**154 466**	**184 134**	**32 577**	**867 686**

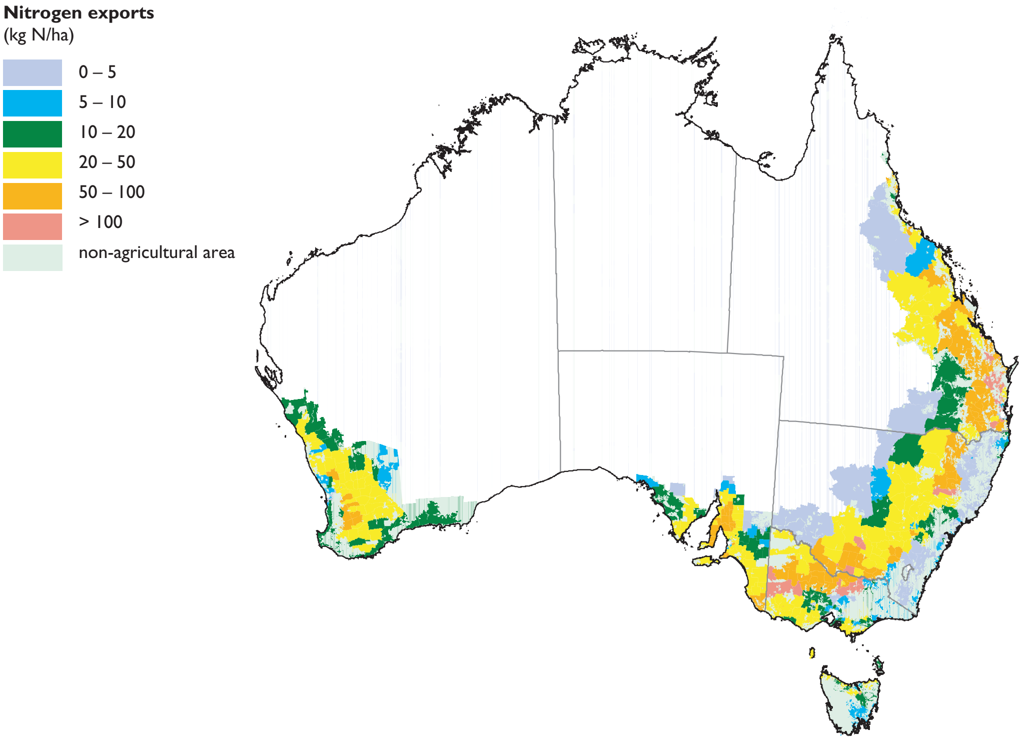
* 1 km^2 =100 ha

** Regional differences in soil organic matter are strongly influenced by climate as well as agricultural farming systems and practices.

Nutrient exports

The amount of nutrient exported each year in agricultural products varies with the nutrient, production levels and with concentration in harvested products. In general, the quantity of each nutrient exported annually from each statistical local area (kg/ha) was: nitrogen >> potassium > phosphorus and calcium > sulfur > magnesium (Figures 3.7, 3.8, 3.9).

Figure 3.7 Nitrogen exports by statistical local area (averaged over 1992–1996).



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 3.8 Phosphorus exports by statistical local area (averaged 1992–1996).

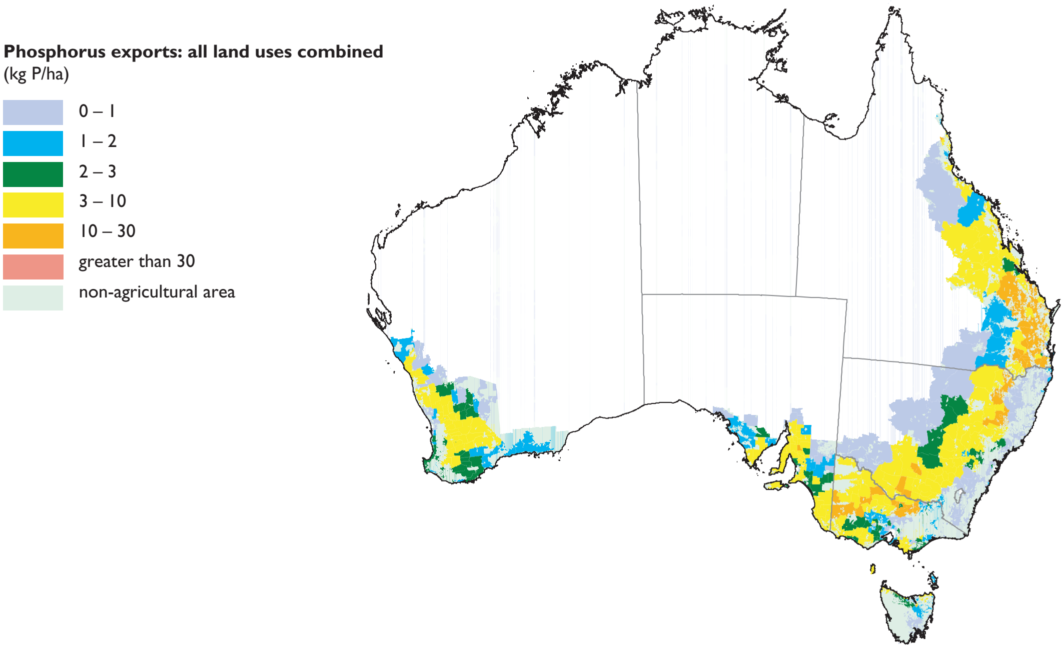
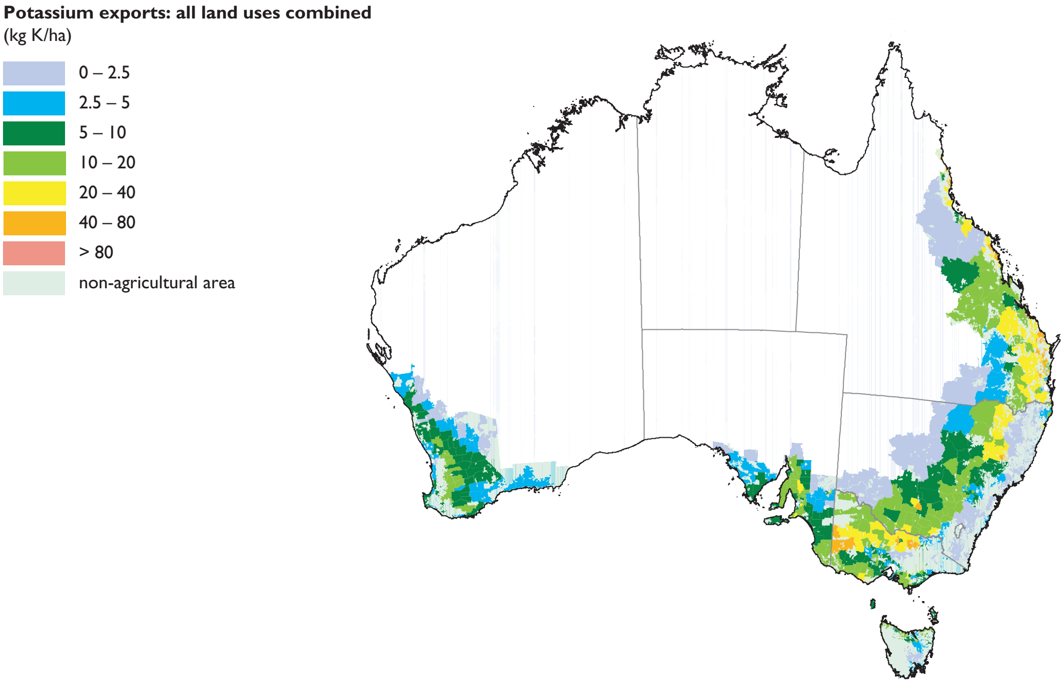


Figure 3.9 Potassium exports by statistical local area (averaged 1992–1996).



Broad observations include:

- Lower nutrient exports occurred in the more arid cropping regions in most States; on the northern slopes of the Great Dividing Range (Victoria); coastal and Tableland regions of New South Wales; the Central Highlands/Southern Midlands of Tasmania; and western parts of the Burdekin basin.

Highest nutrient exports occurred usually from dryland regions of higher productivity and from irrigated areas including:

- Western Australia: western parts of the Great Southern region and parts of the Central wheat belt
- South Australia: Yorke Peninsula, Mid North and the Lower and Mid South East regions
- Victoria: Wimmera (nitrogen and potassium) and northern irrigation areas
- Tasmania: north-western coastal regions
- New South Wales: Riverina (nitrogen, phosphorus, potassium, sulfur and magnesium), South west slopes and North west Slopes and Plains
- Queensland: South eastern Queensland, often extending to the Central Highlands

High calcium exports usually occurred in dairying regions, but were low in most cropping areas, except the south western slopes of New South Wales. High potassium exports existed in regions where sugar cane was produced and high sulfur and magnesium exports were prominent in regions of south eastern Queensland.

Nutrient status and balance

Results on farm gate nutrient balance were grouped broadly into two dominant land use classes (the mixed cropping–livestock zone; and the higher rainfall or more intensive grazing zone). From this some general patterns emerged for each State (Table 3.2). Collectively, these provide both positive and negative signals for future nutrient management in Australia.

Table 3.2 Generalised State assessments of farm gate nutrient balance for two broad land uses within Australia's agricultural zone.

Nutrient	Western Australia	South Australia	Victoria	Tasmania	New South Wales	Queensland*
Grazing						
Nitrogen	positive	positive	variable	neutral/positive	positive/neutral	negative
Phosphorus	positive/neutral	neutral/negative	neutral/positive	positive	positive/neutral	negative
Potassium	negative/positive	negative	positive/negative	neutral/positive	neutral/negative	negative
Sulfur	positive	positive/neutral	positive/neutral	positive	positive/neutral	negative
Calcium	positive	positive	positive	positive	positive	negative
Magnesium	neutral	negative	neutral/negative	neutral	neutral	negative
Cropping						
Nitrogen	positive/neutral	neutral/negative	negative	positive	neutral/positive	negative/neutral
Phosphorus	neutral/positive	neutral	negative/neutral	positive	neutral/negative	negative
Potassium	negative	negative	negative	neutral	negative	negative
Sulfur	positive/neutral	neutral/positive	neutral/positive	positive	neutral/positive	negative/neutral
Calcium	positive	neutral/positive	positive/neutral	positive	positive/neutral	negative/neutral
Magnesium	negative/neutral	negative	negative	neutral	negative/neutral	negative/neutral

* Atherton Tableland in Queensland had positive nitrogen, phosphorus, potassium and calcium balances.

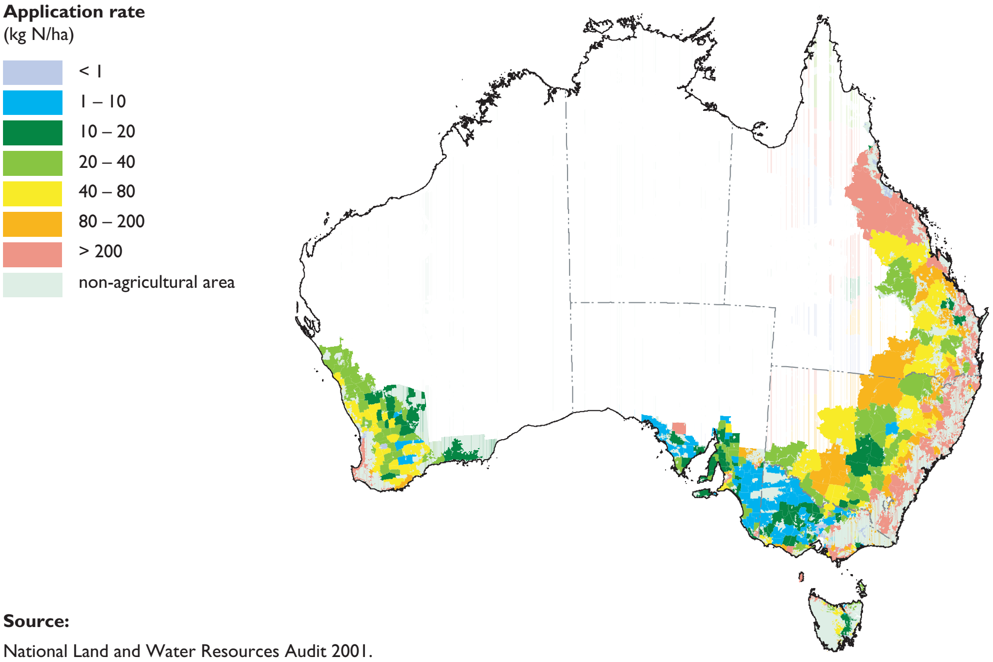
Nitrogen

Nitrogenous fertiliser was used mainly on crops, sugar cane and in horticulture (Figure 3.10). Negligible amounts were applied to dryland pastures (Figure 3.11), but it was used on irrigated pastures, mainly for dairying and hay/silage production. Legumes contribute in a major way to soil nitrogen reserves (Figure 3.5).

The scale of use of nitrogen and level of its application in the cropping zone appears to have increased (Figure 3.10). Use depends on seasonal rainfall conditions that encourage farmers to apply nitrogen to optimise yields and protein grades in wheat (premiums have been paid for high protein wheat since 1989).

- Nitrogen balances varied from neutral to moderately positive for both grazing and cropping land use systems (Figure 3.12). Negative balances existed in Queensland, the Wimmera, Mallee and north-west regions of Victoria (where low levels of nitrogen fertiliser were used); the north-west Slopes and Plains (New South Wales); and parts of South Australia. These regions also often had low or moderate soil organic matter status (Figure 3.6).
- Positive balances existed in regions where dairying and horticulture and major forms of land use occurred.

Figure 3.10 Nitrogen fertiliser application rates (kg N/ha) for **crops** by statistical local area (averaged 1992–1996).



Source:

National Land and Water Resources Audit 2001.

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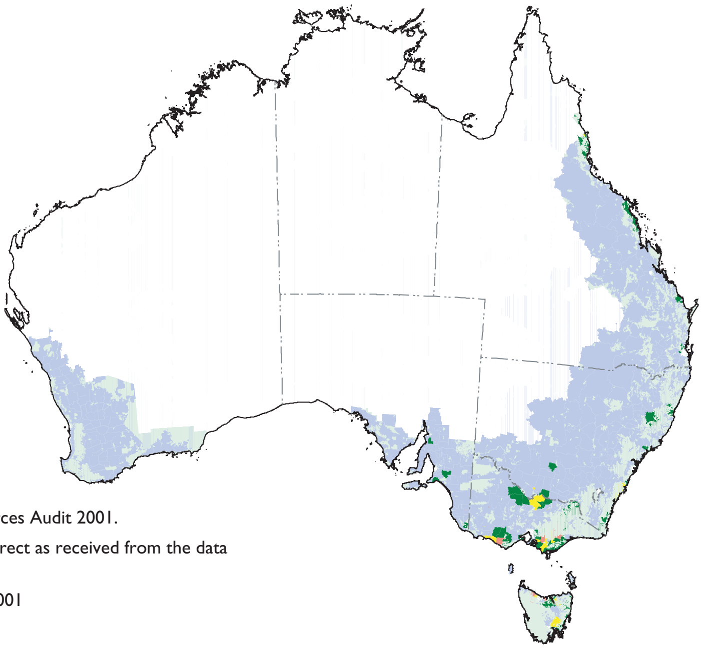
Figure 3.11 Nitrogen fertiliser application rates (kg N/ha) for **pastures** by statistical local area (averaged 1992–1996).



Application rate
(kg N/ha)

- 🟦 < 1
- 🟩 1 – 5
- 🟨 5 – 10
- 🟥 > 10
- ⬜ non-agricultural area

Source:

National Land and Water Resources Audit 2001.

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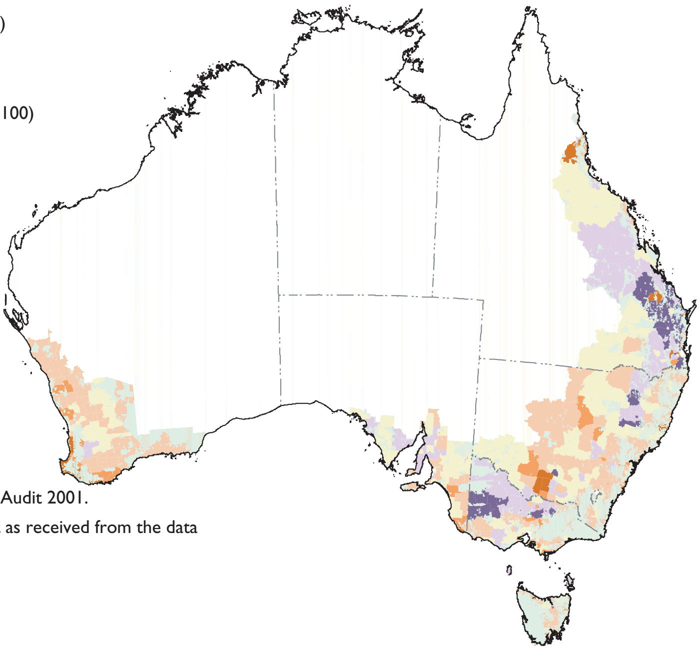
Figure 3.12 Farm gate nitrogen balance (kg N/ha) for **all land uses combined** (averaged 1992–1996).



Nitrogen balance
(kg N/ha)

- 🟪 negative (< -50)
- 🟪 slightly negative (-10 to -50)
- ⬜ neutral (0 ± 10)
- 🟧 slightly positive (10 to 50)
- 🟧 moderately positive (50 to 100)
- 🟧 highly positive (100 to 250)
- 🟫 extremely positive (> 250)
- ⬜ non-agricultural area

Source:

National Land and Water Resources Audit 2001.

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DAIRY

Nitrogen, phosphorus and potassium balances for the Victorian Gippsland region

Prepared by J. White (Market Development Agronomist, Canpotex) and C. Gourley (Department of Natural Resources and Environment, Victoria)

Using published data and industry statistics for the Gippsland dairy region of Victoria, partial nutrient balances for nitrogen, phosphorus and potassium were estimated to be positive for a 'typical' dairy farm. This study confirmed the positive farm-gate nutrient balance findings presented for this region of Victoria. It also demonstrated that appreciable quantities of these nutrients are fed as supplementary feeds and are voided as excreta in laneways and dairy sheds.

Industry profile

- In 1998/99, milk production from the Gippsland region was 1881 million litres, (19% of national production) with a gross farm-gate value of $575 million. Ninety-two percent of milk produced in the region is used in the manufacture of value-added dairy products.
- In recent years, milk production has increased by 3.3% annually, with farm herd size and milk production per cow increasing annually by 7.9% and 2.8% respectively. Average milk production per cow is 4600 L. The average stocking rate is 2 cows/ha.
- Average annual rainfall for the region is 630 mm (but in some areas exceeds 1100 mm). Pasture composition is predominantly rye-grass and clover.
- Deteriorating quality of waterways is recognised as a regional problem, and nutrient management on dairy farms is being actively researched.

This case study calculates partial nutrient balance of nitrogen, phosphorus and potassium for a 'typical' dairy farm in the Gippsland region.

Data sources and assumptions

Nutrient inputs

- Nitrogen fixing varies widely with seasonal conditions and pasture composition. For this case study an average value of 80 kg/ha was used (Eckard et al. 2001).
- Fertiliser inputs were 20 kg N/ha and 25 kg P/ha and 30 kg K/ha (regional farm survey, Gourley et al. 1998, Gourley pers. comm.)
- Nutrients accessed in rainfall (Greenhill et al. 1983, Eckard et al. 2001)
- Annual pasture production was estimated as 12 000 kg/ha with a nutrient content of 3.0% nitrogen, 0.3% phosphorus and 3.0% potassium. Pasture utilisation of 65% was assumed.
- 500 kg of grain supplements (containing 1.9% nitrogen, 0.4% phosphorus and 0.4% potassium) and 600 kg of imported hay (containing 2.5% nitrogen, 0.3% phosphorus and 1.7% potassium) were fed annually to each cow.

Nutrient exports and losses

- Milk production was 5000 L/cow, containing 0.6% nitrogen, 0.08% phosphorus and 0.2% potassium.
- Nutrient losses through the transfer of excreta to non-productive areas (yards, laneways and around troughs) were related to the amount of time cows spent in these areas and were estimated at 10% (Hancock 1950).
- Percentage of ingested nutrients voided in dung were estimated as 20% nitrogen, 60% phosphorus and 12% potassium (Davies et al. 1962).
- Percentage of ingested nutrients voided in urine was estimated as 50% nitrogen, no phosphorus and 80% potassium (Davies et al. 1962).
- Losses through ammonia volatilisation were calculated as 15% of the nitrogen in urine and 3% of the nitrogen in dung (Evans et al. 1998).

- Leaching losses were estimated as 30 kg N/ha (Ledgard et al. 2000), no phosphorus and 10 kg K/ha (Carey & Metherell 1999).
- Run-off losses were estimated as 4 kg N/ha, 4 kg P/ha (*Dairy Farms Annual Report 1998/99*) and 1 kg K/ha (Hosking 1986).

Denitrification losses of nitrogen, and fixation of applied fertiliser phosphorus and potassium were not considered.

Partial nutrient balance (kg/ha)

The partial nutrient balance sheet on an annual per hectare basis is shown in Table 3.3.

- All nutrients were in positive balance.
- Import of supplementary feed represented an appreciable input of nutrients to the dairying system.
- Internal transfer losses of nitrogen and potassium are considerable. On some dairy farms, nutrients from dairy shed effluent are re-applied to pastures, which would lessen the nutrients lost in excreta transfer. However, application of effluent must be undertaken with care to avoid over-application of nutrients to a limited area of the farm.

Implications for industry

- Transfer of nutrients in excreta, or in preserved feed will impact on the distribution of nutrients within the dairy farm system.
- Quantities of nutrients moving due to fixation, leaching, run-off and atmospheric losses are difficult to estimate; and vary markedly with seasonal conditions. They can be appreciable and will impact on nutrient budgets designed for determining maintenance fertiliser requirements for dairy farms and on off-site nutrient leakages.

Table 3.3 Nitrogen, phosphorus and potassium partial balances for a typical Gippsland dairy system expressed as kg nutrient/ha on an annual basis.

Input/loss mechanism	Nitrogen (kg/ha)	Phosphorus (kg/ha)	Potassium (kg/ha)
Inputs			
Fertiliser	20	25	30
Rainfall	3	<1	4
Legume nitrogen fixation	80		
Supplementary feed	49	7	28
Outputs			
Product (milk)	60	8	20
Excreta transfer	20	2	24
Volatilisation	23		
Leaching	30	0	10
Run-off	4	4	1
Balance	15	19	7

Phosphorus

Status

Australia has a long history of phosphorus fertiliser application and the phosphorus status of most agricultural soils has been raised (Figure 3.13, Table 3.4).

- 1.4 million hectares of agricultural land (estimate only) still had very low surface soil phosphorus levels (< 10 mg/kg Colwell extractable soil phosphorus). These areas tended to be mainly in the drier regions in each State, where lower input farming is practised and were especially evident in South Australia.
- 24.6 million hectares—across all States—and making up 28% of the land assessed (estimate only), had soils of marginal phosphorus status (10 to 20 mg/kg extractable soil phosphorus).
- 3.2 million hectares had high values (> 80 mg extractable P/kg), located mainly in Queensland, New South Wales and Victoria. Intensive, irrigated agriculture, especially dairying and horticulture are often located in areas with naturally higher fertility status soils. Levels are augmented with fertiliser application.

Balance estimates

Phosphorus applications appear to be directed to the cropping phases of rotations, with many pastures relying on residual soil phosphorus reserves (Figures 3.4, 3.14). Phosphorus fertiliser use on dryland pastures is low (< 5 kg P/ha). It was higher on irrigated pastures. More phosphorus is applied in cropping regions with more reliable rainfall than in the more arid cropping regions (Figure 3.4).

The phosphorus balance was estimated to be either neutral or slightly positive over large areas of the agricultural zone (Figure 3.15).

- Moderate to highly positive balances existed in regions of Victoria and Tasmania, where dairying and horticulture are the main forms of land use. These regions also had mainly moderate to high soil phosphorus status.
- Negative balances occurred in major regions of Queensland, the Wimmera and northern slopes of the Great Dividing Range of Victoria and the Riverina and northern Slopes of New South Wales. In most of these regions, soil phosphorus status was assessed as marginal.

Table 3.4. Estimated areas of land (km^2)* having specified Colwell soil phosphorus ranges (mg P/kg)

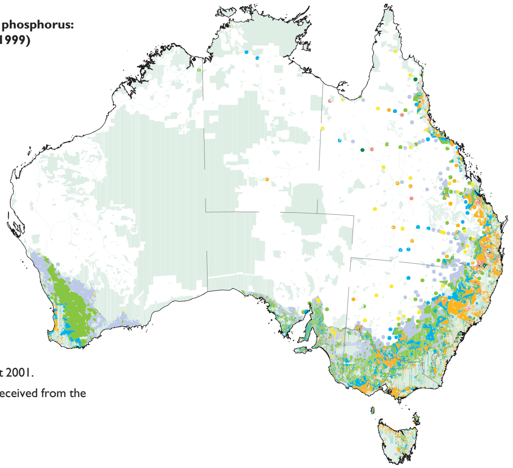
State	< 10	10 – 20	20 – 30	30 – 40	40 – 80	80 – 150	> 150	Total area
Queensland	2 358	21 768	24 070	21 230	42 326	11 481	2 485	125 718
New South Wales	1 835	61 963	89 469	58 656	65 304	9 003	2 772	289 001
Victoria	219	30 669	47 382	28 597	30 724	3 434	490	141 515
Tasmania	333	1 600	3 842	3 500	6 799	956	157	17 188
South Australia	8 035	49 427	39 154	17 740	9 016	636	137	124 148
Western Australia (sw)	1 183	80 816	94 838	14 028	5 824	4	0	196 703
Northern Territory	0	62	12	18	167	128	87	474
National	**13 963**	**246 305**	**298 767**	**143 769**	**160 170**	**25 642**	**6 130**	**894 747**

*1 km^2 =100 ha

Figure 3.13 Distribution of topsoil phosphorus determined by commercial soil testing (1989–1999).

Interpolated surface for soil Colwell phosphorus: (all depths to 15 cm, sampled 1990–1999)
(mg/kg)

🟨 < 10
🟦 10 – 20
🟩 20 – 30
🟦 30 – 40
🟧 40 – 80
🟥 80 – 150
🟩 > 150
⬜ non-agricultural area



Source:

National Land and Water Resources Audit 2001.

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Figure 3.14 Phosphorus fertiliser application rates (kg P/ha) for pasture by statistical local area (averaged 1992–1996).

Phosphorus Fertiliser application rates (pasture)
(kg P/ha)

🟦 < 1
🟦 1 – 5
🟩 5 – 10
🟨 10 – 15
🟥 > 15
⬜ non-agricultural area

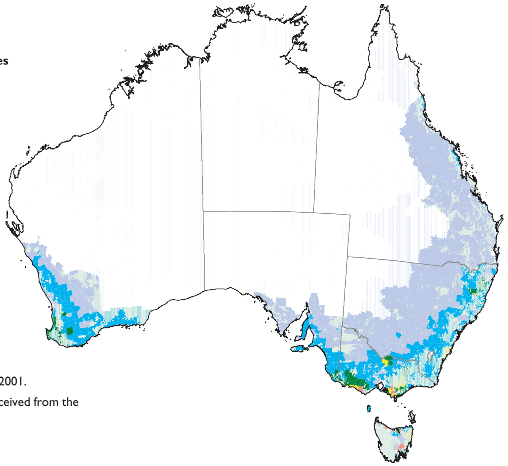

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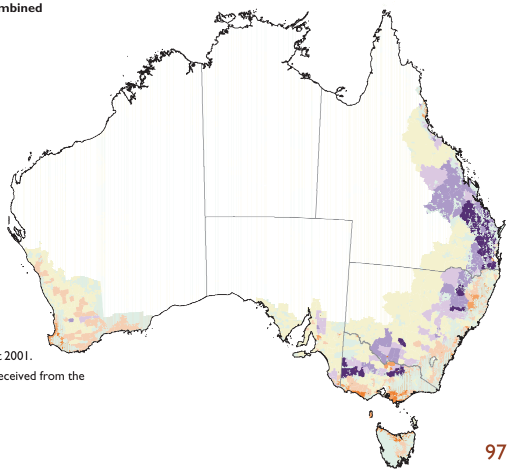
Figure 3.15 Farm gate phosphorus balance (kg P/ha) with all land used combined (averaged 1992–1996).

Phosphorus balance: all land uses combined
(kg P/ha)

🟪 highly negative (< -10)
🟪 moderately negative (-5 to -10)
🟪 slightly negative (-2 to -10)
⬜ neutral (0 ± 2)
🟧 slightly positive (2 to 5)
🟧 moderately positive (5 to 10)
🟧 highly positive (10 to 20)
🟧 very highly positive (20 to 50)
🟫 extremely positive (> 50)
⬜ non-agricultural area



Source:

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INTENSIVE HORTICULTURE

Nitrogen and phosphorus balances for banana plantations in northern Queensland

Prepared by P.W. Moody, Queensland Department of Natural Resources and Mines (Queensland)

Detailed study of nitrogen and phosphorus fluxes in a plant and ratoon banana crops grown in northern Queensland under irrigation showed a positive nitrogen balance (*with substantial leaching and gaseous losses of applied nitrogen*) and a positive phosphorus balance in the plant crop and a small negative phosphorus balance in the subsequent ratoon crop. New industry guidelines for managing nitrogen and phosphorus inputs are now being actively promoted within the industry (see also banana case study on soil acidification).

This report compares estimates of complete nutrient balance for nitrogen and phosphorus with estimates derived for partial balances (fertiliser inputs minus nutrients removed in harvested bananas)

Industry profile

- Bananas are grown on 6000 ha of the wet tropical coast of north Queensland (annual rainfall is over 3000 mm), and are supplemented during crop growth with either overhead watering systems, or under-tree mini sprinkler or trickle irrigation systems (Daniells 1995).
- With overhead irrigation, nitrogen and potassium fertilisers are side-dressed, generally at 4–8 week intervals. For mini-sprinklers or trickle irrigation they are applied through fertigation at intervals ranging from every irrigation (1–2 days during hot weather) to once a fortnight (Daniells 1995).
- Phosphorus fertilisers (superphosphates or NPK fertiliser blends) are usually broadcast at six-monthly intervals. Some growers only apply large rates of phosphorus at planting.
- A recent industry survey indicated that average annual levels of nutrient addition were: 519 kg N/ha, 68 kg P/ha and 750 kg K/ha (Daniells 1995).

Experimental details

A 0.1 ha area of contoured bananas grown on a well-drained ferrosol (clay loam) at South Johnstone in northern Queensland was instrumented to intensively monitor and quantify nitrogen and phosphorus fluxes and off-site losses under typical management practices (Moody et al. 1996).

Measurements included:

- nitrogen and phosphorus fertiliser input;
- nitrogen and phosphorus removal in harvested bunches;
- change in soil nitrogen and phosphorus reserves; and
- losses of nitrogen and phosphorus by drainage and runoff in the plant and first ratoon crop.

Fertiliser inputs comprised 238 kg N/ha and 138 kg P/ha to the plant crop and 232 kg N/ha and zero phosphorus to the ratoon crop, which are levels well below industry practice. Fertilisers were side dressed at 6 weekly intervals with irrigation supplied via overhead sprinklers. Nitrogen and phosphorus were applied as urea and triple superphosphate.

Nitrogen balance

Nitrogen balances for the plant and first ratoon crops (Figure 3.16) show:

- The contribution from soil nitrogen reserves was considerable, but about a third of the nitrogen accumulated by the crop
- large leaching losses of nitrogen under both crops
- large gaseous losses of nitrogen (volatilisation and/or denitrification) in the first ratoon crop.

Partial balance estimates indicate the system was in positive (inputs > exports) nitrogen balance (208 kg N/ha in the plant crop and 159 kg N/ha in the first ratoon). However, a considerable amount of this either existed in the crop biomass (and can therefore be recycled to subsequent crops) or was lost through leaching and gaseous losses.

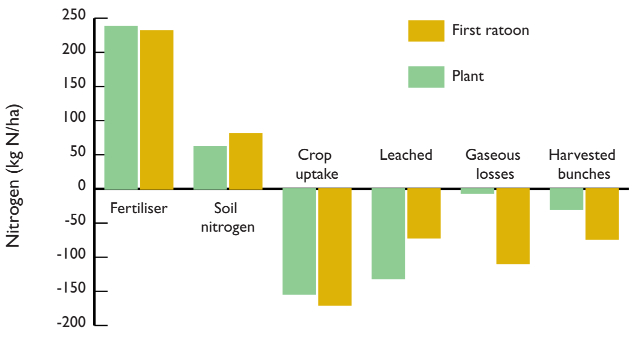
Losses reported are for much lower application levels than are currently practised of (519 kg N/ha) (Daniells 1995). Losses in typical plantations are likely to be considerably higher than those measured in the experiment. A positive (partial) nitrogen balance may indicate potential off-site nitrogen losses through either leaching, runoff, volatilisation or denitrification.

Phosphorus balance

Phosphorus balances for the plant and first ratoon crops (Figure 3.17) indicate:

- an increase in soil phosphorus reserves under the plant crop (indicated as a negative value because the soil is acting as a sink for applied phosphorus) and a decrease under the first ratoon, as the crop utilised the soil phosphorus reserves (indicated as a positive value since now the soil is a phosphorus source).
- a small removal of phosphorus in harvested bananas compared to the quantity of fertiliser applied.

Figure 3.16 Nitrogen balance (kg N/ha) in plant and first ratoon banana crops.



Partial balance estimates indicate a positive balance (inputs > exports) of 135 kg P/ha for the plant crop and a negative balance (inputs < exports) of 6 kg P/ha for the first ratoon. Calculated over both crops, the partial nutrient balance was highly positive.

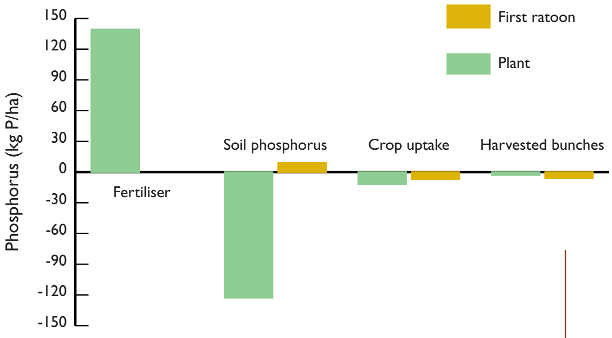
Current industry practice is to apply an average of 68 kg P/ha to the plant crop and little more phosphorus to the next four ratoon crops (Daniells 1995). For this system, the overall partial balance for phosphorus would still be positive.

The complete balance at the experimental site indicated that phosphorus accumulates in the soil, with negligible losses by leaching (the soil at the experimental site was highly phosphorus sorbing) or run-off (the site was contoured).

Implications for the industry

- The industry is aware of the need to match fertiliser inputs to crop demands. Efficient nitrogen management should employ crop growth monitoring and appropriate fertigation systems. Regular soil testing to monitor soil phosphorus reserves offers the best approach for managing the positive partial balance for phosphorus.

Figure 3.17 Phosphorus balance (kg P/ha) in plant and first ratoon banana crops.



Potassium

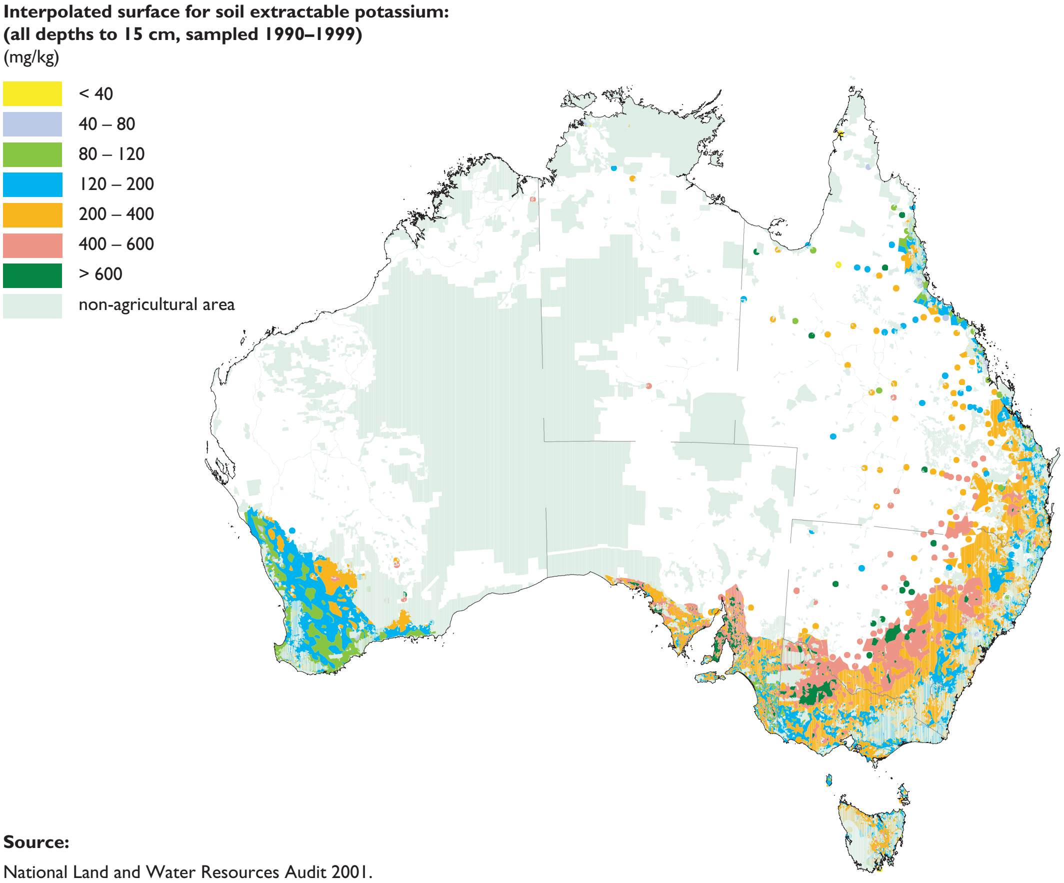
Status

Most agricultural soils had adequate to high natural reserves of potassium, with inland soils tending to be higher than coastal soils (Figure 3.18, Table 3.5).

- 0.9 million hectares were considered potentially deficient in potassium (< 80 mg K/kg), occurring mainly on sandier soils in all States.
- 7.7 million hectares were assessed as having marginal potassium status (80 to 120 mg K/kg).

In coastal regions of Victoria, soil potassium reserves appeared to be maintained by regular potassium fertiliser applications

Figure 3.18 Distribution of topsoil extractable potassium (mg K/kg) determined by commercial soil testing (1989–1999).



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Balance estimates

Use of potassium fertiliser has continued to increase from a low base (Figure 3.3) and is confined mainly to dairying, horticulture and sugar cane areas (Figures 3.19, 3.20).

Negligible amounts are applied to dryland crops, except in Western Australia where recent research identified potassium deficiency as a major limitation to crop and pasture yield and grain quality. In these regions of Western Australia, potassium balance changed from being negative to neutral or slightly positive as potassium was applied (Figure 3.22).

Potassium has been applied to soils of low potassium status in Queensland and Western Australia. In south-eastern Australia it was also applied to soils of moderate soil potassium status (built up by past potassium applications).

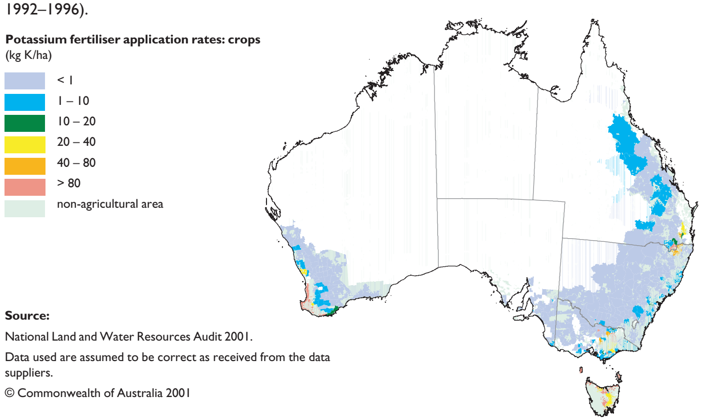
- Estimated potassium balances varied from being moderate to highly negative in regions where no potassium was applied (Figure 3.21). Adequate potassium reserves existed in surface soils in most of these regions (Figure 3.18).
- Neutral potassium balances were confined to coastal regions of New South Wales, the Burdekin basin and more arid cropping regions of New South Wales and southern Queensland (Figure 3.21).

Table 3.5 Estimated areas of land (km^2)* assessed having specified extractable soil potassium ranges (mg K/kg).

State	< 40	40–80	80–120	120–200	200–400	400–600	> 600	Total area
Queensland	61	3 007	10 011	31 023	61 021	10 867	248	116 238
New South Wales	17	478	4 866	39 645	141 204	94 461	8 202	288 871
Victoria	0	91	2 273	32 931	60 975	32 134	13 146	141 548
Tasmania	4	207	924	5 580	9 695	994	98	17 502
South Australia	30	2 069	5 932	14 975	52 601	36 355	12 200	124 163
Western Australia (sw)	0	2 423	53 501	106 012	34 020	768	0	196 725
Northern Territory	47	381	44	0	0	0	0	472
National	159	8 654	77 551	230 166	359 516	175 579	33 894	885 519

*1 km^2 = 100 ha

Figure 3.19 Potassium fertiliser application rates (kg K/ha) for crops by statistical local area (averaged for 1992–1996).

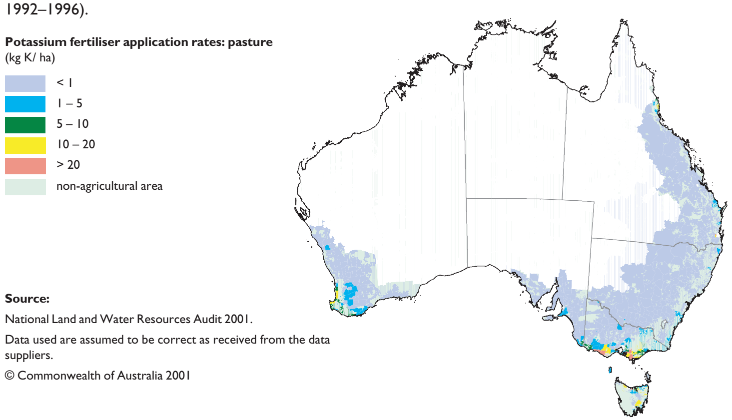


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 3.20 Potassium fertiliser application rates (kg K/ha) for pasture by statistical local area (averaged for 1992–1996).

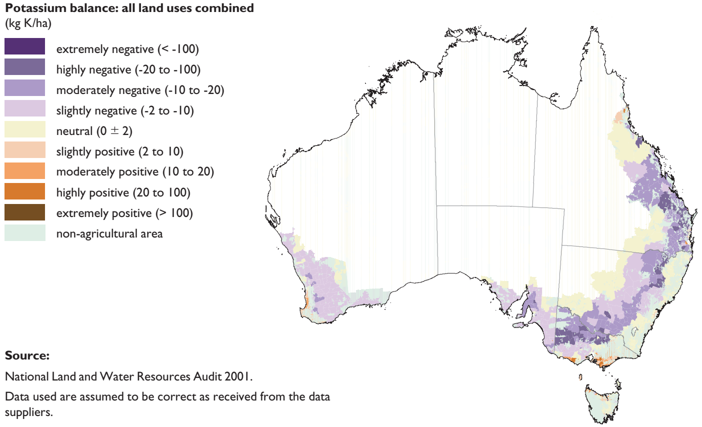


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 3.21 Farm gate potassium balance (kg K/ha) – all land used combined (averaged for 1992–1996).



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

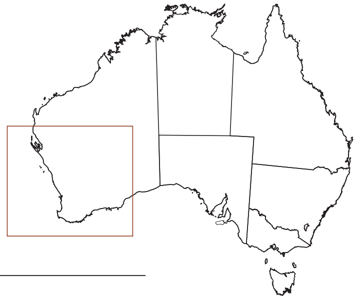
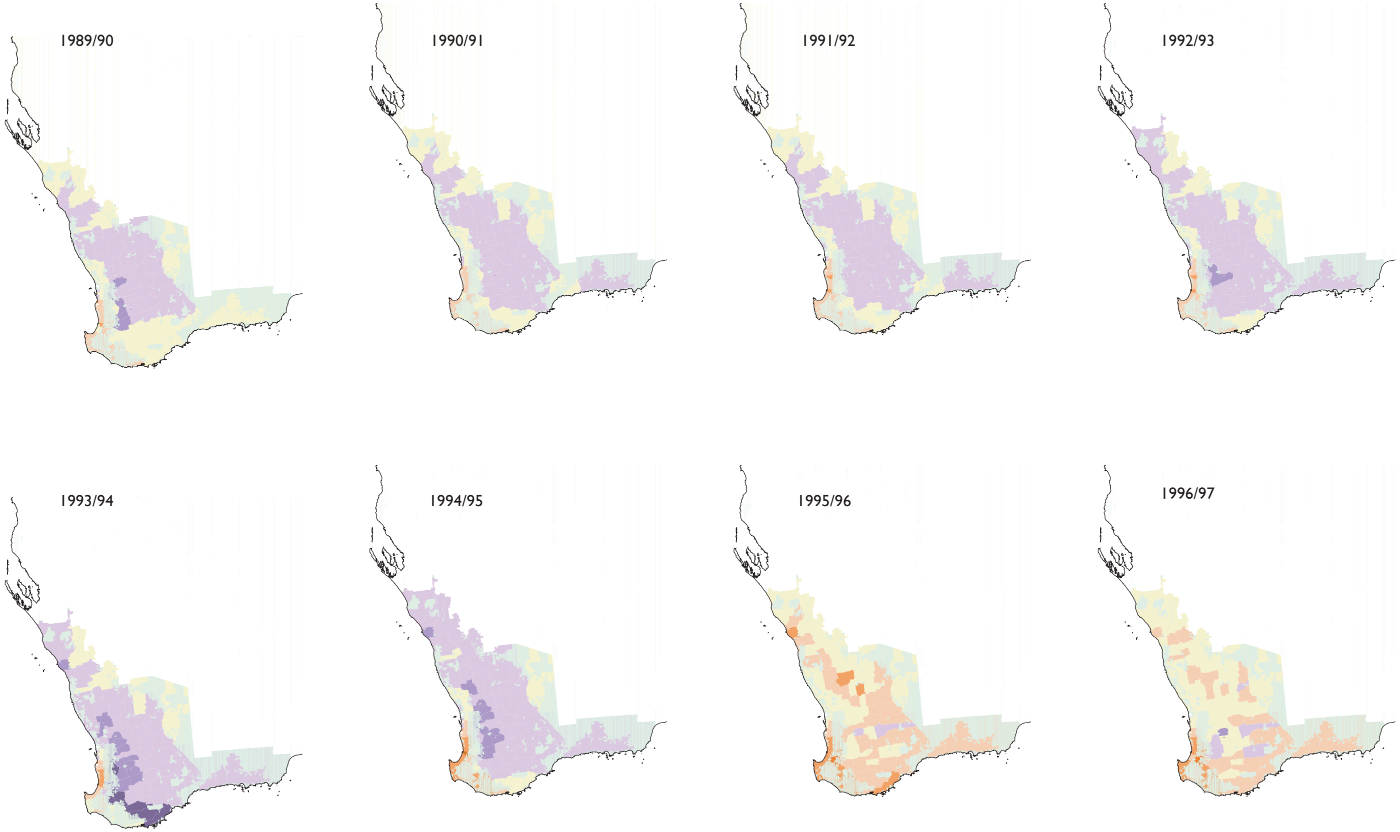


Figure 3.22 Farm gate potassium balance (kg K/ha) for south west regions of Western Australia (1989–1996).

Potassium balance for Southern Western Australia
(kg K/ha)

- 🟪 extremely negative (< -100)
- 🟪 highly negative (-20 to -100)
- 🟪 moderately negative (-10 to -20)
- 🟪 slightly negative (-2 to -10)
- 🟨 neutral (0 ± 2)
- 🟧 slightly positive (2 to 10)
- 🟧 moderately positive (10 to 20)
- 🟧 highly positive (20 to 100)
- 🟫 extremely positive (> 100)
- 🟩 non-agricultural area



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

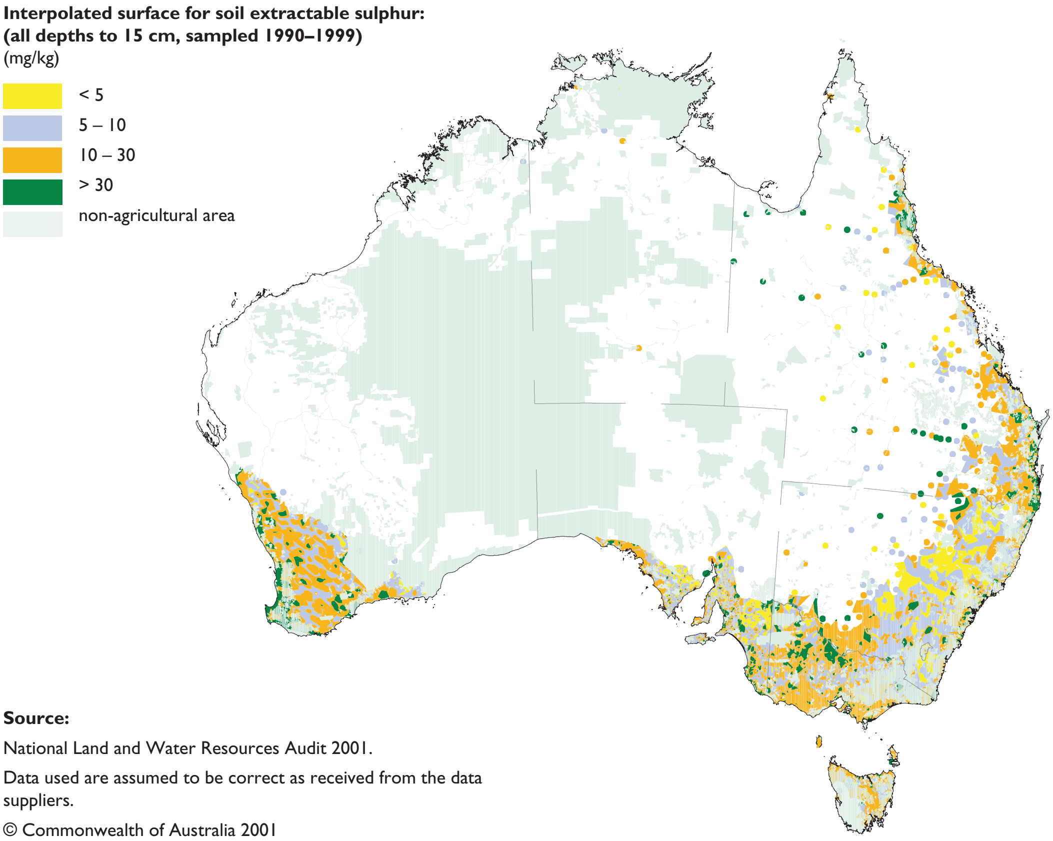
Sulfur

Status

Soils with potentially low sulfur status may occur in South Australia and New South Wales (Figure 3.23), but in these areas substantial sulfur reserves may exist in the subsoil following past applications in superphosphates or gypsum. A surface soil sulfur value of less than 5 mg S/kg may be indicative of sulfur deficiency. Where fertilisers of low sulfur content have replaced traditional applications of superphosphate (containing 10% sulfur) the residual value of soil sulfur should be further examined.

- Large areas of agricultural land had extractable soil sulfur values between 5 and 10 mg S/kg.
- More than 50% of the area assessed had values greater than 10 mg S/kg.
- High sulfate sulfur levels occur in the subsoil (as gypsum accretions) in many semi-arid regions (in which topsoil organic matter and sulfur levels are often low).
- Sulfur inputs also occur through irrigation water and rainfall in coastal areas. Sulfur inputs via rainfall in the inland are low.

Figure 3.23 Distribution of topsoil sulfur (mg S/kg) determined by commercial soil testing (1989–1999).



Source:

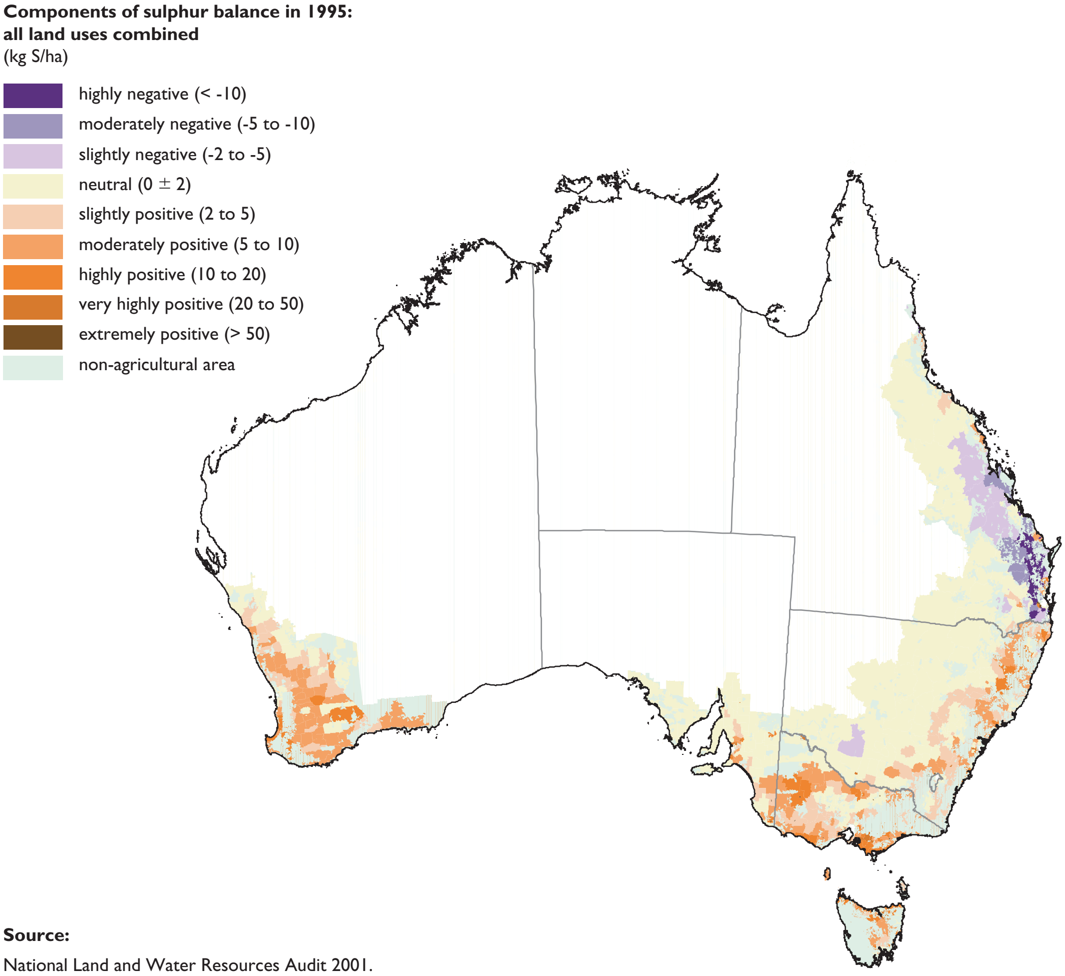
National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Balance estimate

- Sulfur balances produced for 1995/96 (Figure 3.24) mainly varied from being neutral to moderately or highly positive. Negative balances existed in significant areas of Queensland. These differing balances probably relate to the use of superphosphates and gypsum in many regions of Australia and low use in some Queensland regions.
- Regions with neutral sulfur balance sometimes occurred on soils of low or marginal sulfur status.
- Highly positive balances were usually recorded in dairy and horticultural regions, that also had reasonably high soil sulfur status.

Figure 3.24 Farm gate sulfur balance (kg S/ha) in 1995/96 with all land used combined.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Calcium

Status (eastern Australia)

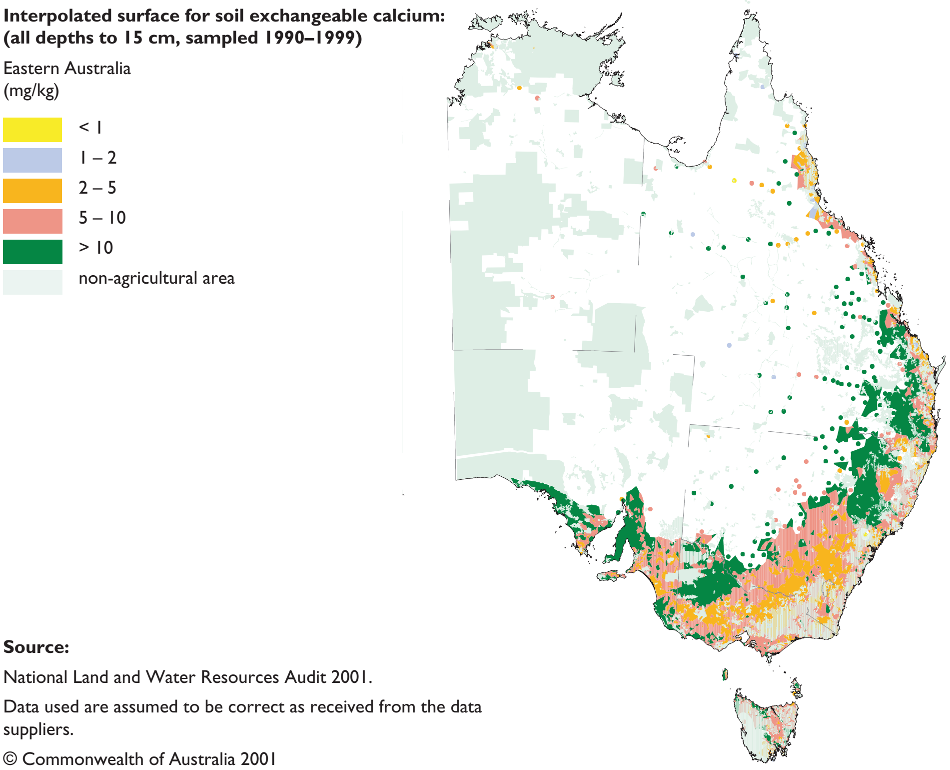
Agricultural surface soils in eastern Australia have good calcium reserves (Figure 3.25). Some potentially low values occurred along coastal regions of Queensland. Reserves of calcium in agricultural soils of Western Australia are unknown and need to be assessed. However, appreciable amounts of calcium may also be added in irrigation water in some areas (e.g. northern Victoria and South Australia).

Balance estimates

Calcium applied to agricultural land comes from fertilisers (e.g. single superphosphate with 10% calcium and triple superphosphate with approximately 15% calcium) and from the soil conditioners (lime with approximately 34% calcium, dolomite ~25% calcium and gypsum ~20% calcium).

- In 1995/96, calcium balances varied from being neutral through to highly positive across southern Australia (Figure 3.26). This can be linked to superphosphate and soil conditioner use.
- Negative balances existed in significant parts of south-eastern and central Queensland, but in these regions the calcium status of surface soils is adequate to high (Figure 3.25).

Figure 3.25 Distribution of topsoil exchangeable calcium (meq Ca/100 g) in eastern Australia (1990–1999).

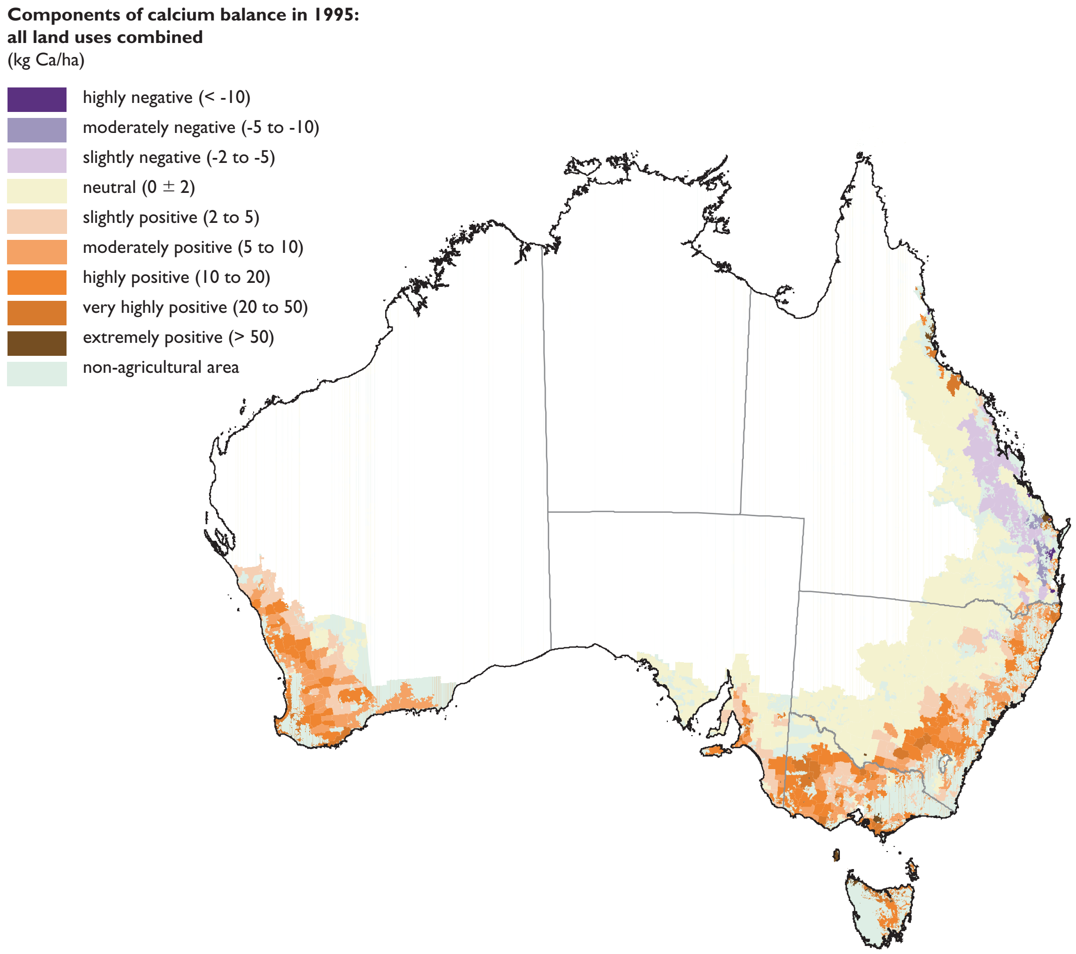


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 3.26 Farm gate calcium balance (kg Ca/ha) in 1995/96 with all land used combined.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Magnesium

Status (eastern Australia)

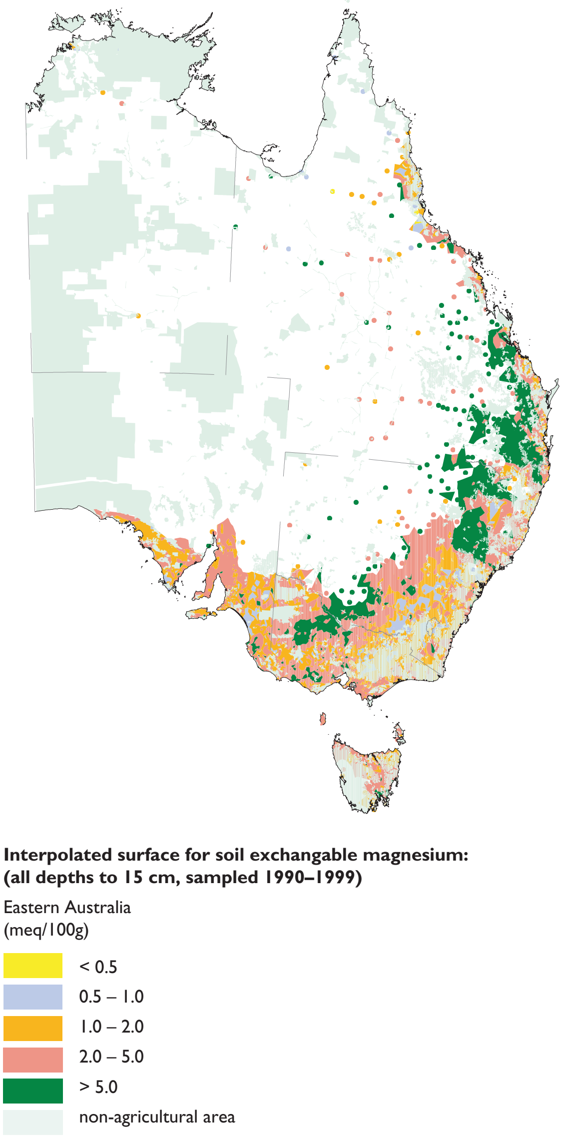
Surface soils in agricultural regions of eastern Australia have good magnesium reserves, although levels are lower than those determined for calcium (Figure 3.27). Some potentially low values may exist along coastal regions of Queensland. Reserves of magnesium in agricultural soils of Western Australia need to be evaluated.

Balance estimates

Magnesium applied to agricultural land comes from fertilisers and dolomite (~7.2% magnesium). Fertiliser applications were mainly confined to horticultural enterprises and some dairy areas. Negligible or very low use occurred elsewhere.

- Magnesium balances were mainly either negative or neutral (Figure 3.28). Negative balances were especially noticeable in Queensland, the Riverina and south-west Slopes of New South Wales and parts of South Australia. These areas are highly productive regions, where negligible magnesium fertiliser was applied, but adequate reserves of magnesium exist in surface soils (Figure 3.27).
- Positive balances existed in dairy and horticultural regions of Victoria, Tasmania and New South Wales.

Figure 3.27 Distribution of topsoil exchangeable magnesium (meq Mg/100 g) in eastern Australia (1990–1999).

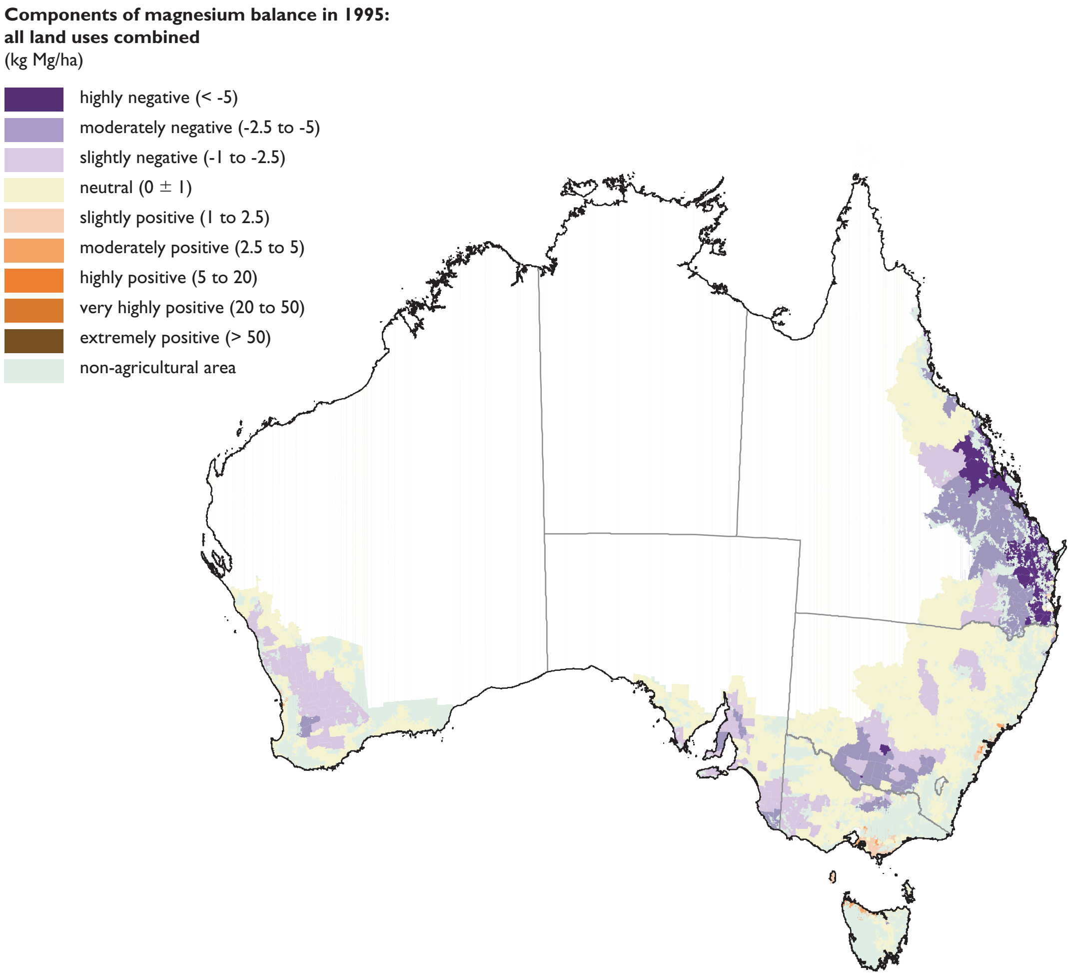


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 3.28 Farm gate magnesium balance (kg Mg/ha) in 1995/96 with all land used combined.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

DRYLAND CROPPING

Nitrogen, potassium, calcium and magnesium balances for dryland cropping systems (Burnett region, Queensland)

Prepared by M.J. Bell, Department of Primary Industries (Queensland) and P.W. Moody, Department of Natural Resources and Mines (Queensland)

Markedly negative partial balances for nitrogen, potassium and magnesium were determined for two cropping rotations commonly used in the inland Burnett region of Queensland. Calcium balances were positive. The depletion of potassium and magnesium was exacerbated by the removal of peanut stubble as hay and by increased frequency of growing high-yielding grain legume crops. Soil testing was recommended to improve fertiliser decisions in this region.

Industry profile

- Dryland cropping occurs over 50 000 ha of predominantly acidic soils in the Inland Burnett region of south-eastern Queensland. The area receives approximately 750 mm rainfall annually, and various summer and winter grain and summer legume crops are grown in rotation. Crops include peanut, soybean, maize, sorghum, wheat, oats and barley.
- Fertilisers are either broadcast (lime or muriate of potash) or band applied below and to the side of the seed at planting. Nitrogen is occasionally side-dressed on grain crops later in seasons where adequate rainfall is anticipated.
- Stubble retention is widely practised, although peanut stubble is occasionally baled for hay. Conventional tillage systems (discs and tined implements) are mainly used, but reduced/zero tillage is becoming increasingly common for crops other than peanuts.

Partial balances

Partial balances are shown for the conventional and intensive rotations over 16 years for nitrogen, potassium, calcium and magnesium in Figure 3.29.

- Nitrogen balances were always negative, and particularly where peanut hay was removed (which contains approximately 2% nitrogen and a high proportion of mineral nitrogen).

  The nitrogen balance was less negative in the intensive rotation than the conventional rotation, and mainly resulted from application of nitrogen to the grain crops (wheat and maize). Poor wheat yields in dry seasons resulted in high residual nitrogen.
- Potassium and magnesium balances were also always negative, with hay removal exacerbating the depletion of soil potassium and magnesium reserves. Considerably more potassium was removed from the soil than magnesium. For both nutrients, the intensive rotation resulted in a greater negative balance than the conventional rotation.
- Calcium balance was positive where no hay was removed, because calcium was applied to peanut and soybean as superphosphate or triple superphosphate. Indeed, the calcium balance is actually considerably more positive, since no allowance has been made (Figure 3.29) for applications of lime to correct soil acidification (farmers use approximately 2.5. t/ha every five years).

Effect of crop type and crop yield on partial potassium balance

Farmers generally apply rates of fertiliser sufficient for the ‘average’ district yield. In good yielding seasons, this may result in under-fertilisation, and a greater reliance on soil nutrient reserves. Because legumes have higher concentrations of nutrients in harvested seed/pods than grain crops, an above average legume crop will decrease soil reserves more than an above average grain crop.

Figure 3.30 indicates the impact of individual grain and legume crop yields on partial potassium balance, with the intercept (i.e. zero partial balance) indicating the yield at which fertiliser input equals harvested product removal. These intercepts are close to the average district yields of individual crops.

Over the period 1983–1999, soybean and peanut crops required more potassium than was applied in six out of eight crops, while maize required more potassium than was applied in all crops. However, a greater discrepancy exists between applied fertiliser potassium and potassium removed in good seasons for legumes than grain crops. If the frequency of legume crops in the rotation increased, then an increased potential exists for greater depletion of soil nutrient reserves at the current levels of fertiliser use. Implications of the nutrient balance for the region:

- Potassium and magnesium deficiencies are likely to become increasingly important limitations to productivity because soil reserves are making up the deficit between fertiliser input and crop nutrient removal.
- Increasing legume frequency in rotations is likely to exacerbate the decline in soil potassium and magnesium reserves, particularly when yields are above average.
- Better seasonal weather forecasting is required to allow fertiliser inputs to match crop yield.
- Monitoring soil nutrient reserves by regular soil sampling will allow fertiliser inputs to be adjusted to maintain soil nutrient levels.
- Where potassium balances are negative, subsoil potassium levels are likely to decline. Potassium taken up be plant roots will be transferred to the above-ground parts, and returned to the surface layers of the soil in crop residues.

Figure 3.30 Relationships between potassium balance and yield of soybean, peanut and maize crops grown in rotation between 1983 and 1999.

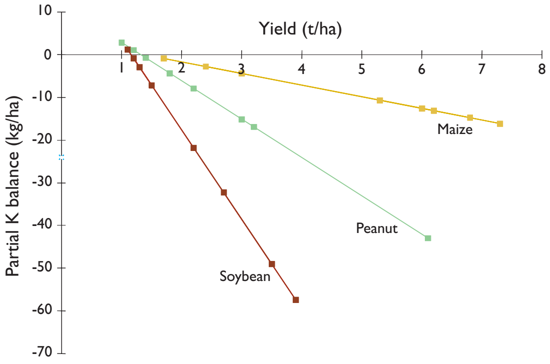
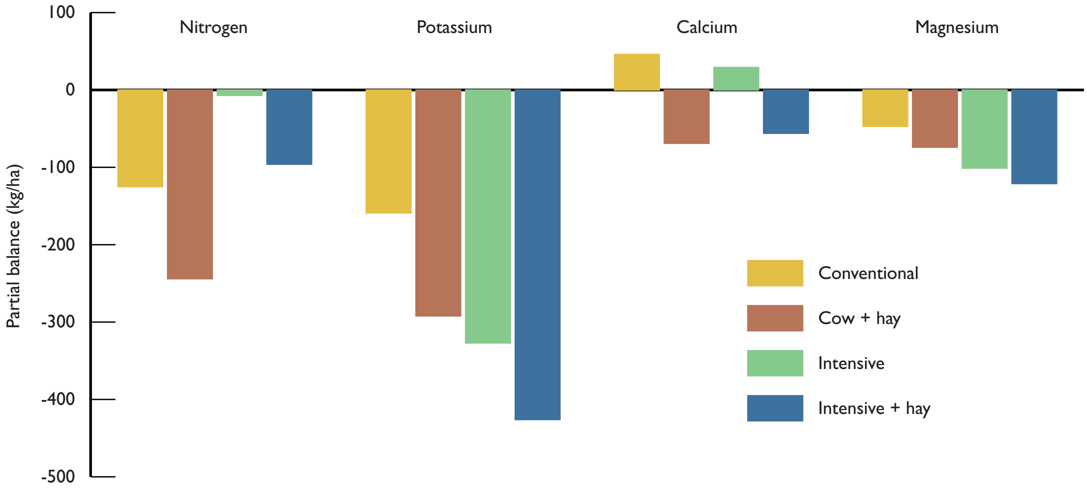


Figure 3.29 Partial nutrient balances (nitrogen, potassium, calcium, magnesium) over a period of 16 years for conventional and intensive rotations of dryland crops with and without the removal of peanut hay from every third peanut crop.



RICE

A nutrient audit of the Australian rice industry

Prepared by G. Batten, Charles Sturt University, M. Unkovich, Agriculture Victoria, and D.J. Reuter and C. Kirkby, CSIRO Land & Water, with assistance from Jan Hubatka and Susan Ciavarella, Agriculture NSW

In a single year assessment of nutrient balance in the southern New South Wales rice growing region, industry data showed negative nitrogen, phosphorus and potassium balances, and positive sulfur, calcium and magnesium balances. The nitrogen, phosphorus and potassium balances became substantially more negative where rice stubbles were burnt—a standard industry practice.

Industry profile

- The Australian rice industry started in southern New South Wales in 1925 and has shown continued growth in area sown, crop yield and hence total production throughout its history.
- Yields per hectare of rice are amongst the highest in the world. Average yields for Amaroo—the variety grown in the northern Murrumbidgee Irrigation Area—have exceeded 10 t/ha in several years, with individual producer yields as high as 15 t/ha. These high yields result in significant removal of essential plant nutrients.
- Australian farmers produce over one million tonnes of paddy rice each year from about 150 000 ha of land. At present, 10 commercial rice varieties are grown.
- Rice is generally grown in a rice–winter cereal–pasture rotation, where the pasture phase provides an opportunity to increase soil nitrogen reserves through legumes (~50 kg/ha, Peoples et al. 2000). In some areas, (20 % of rice crops) five or more rice crops are grown consecutively. Heavy rice stubbles are usually burnt.
- Nitrogen is applied at levels that optimise grain yield. The largest responses to nitrogenous fertiliser are obtained when the nitrogen is applied just before the crop is planted or immediately before permanent water is applied. Currently, no reliable soil test exists to guide rice growers on how much nitrogen to apply at these times. Applications of nitrogen at the panicle initiation are also used in conjunction with a shoot analysis service.
- Where continuous rice is grown, growers now apply 20 kg P/ha. Yield decreases occur where only 10 kg P/ha is used.

Data sources

- Nutrient inputs and removals were determined for the crop grown in the 1998/1999 season, which achieved an industry average yield of 9.3 t/ha (at 14% moisture content).
- Nutrients applied as fertiliser were calculated from information supplied by rice growers who used the NIR Tissue Testing Service operated by Ricegrowers' Co-operative Limited (Blakeney et al. 1994, Batten et al. 2000). This service is used by over 40% of rice producers.
- Average concentrations of nutrients in irrigation water used for the summers of 1998 and 1999 at the Narranderra regulator and the Sturt Canal offtake were supplied by Murrumbidgee Irrigation Limited, Leeton. The average use of irrigation water was 13.3 ML/ha (data supplied by Murray and Murrumbidgee Irrigation Limited).
- Nutrients in grain and stubble were provided from published data for Australian rice crops (Marr et al. 1995, 1999). Nutrients input in seed were calculated using seeding rate data taken from RiceCheck records for the 1998–1999 crop (J. Lacy pers. comm.).
- Losses due to stubble burning were estimated using data summarised by Kirkby (1999).
- Losses of applied nitrogen fertiliser via denitrification and ammonia volatilisation were estimated from Australian research (Bacon & Heenan 1987, Simpson et al. 1988) as 35% of the level of nitrogen applied.

Partial nutrient balances

Balances derived from these data sets are presented in Table 3.6.

Nutrient inputs

- Inputs were mainly derived from fertilisers and nutrient contaminants in irrigation water.
- Nitrogenous fertilisers—applied at a level to optimise yield—were typically 120 kg N/ha in 1998/99.
- Significant loads of sulfur (18 kg S/ha), calcium (25 kg Ca/ha) and magnesium (15 kg Mg/ha) were derived from irrigation water, with lower loads for nitrogen and phosphorus.

Nitrogen gaseous loss estimates

- Calculated as a conservative value of 42 kg N/ha

Nutrient exports

- Quantities of nutrient exported in harvested grain varied from 93 kg N/ha to 2.2 kg Ca/ha. Large amounts of nitrogen, phosphorus, and potassium were removed in grain.
- Where rice stubbles are burnt, large quantities of potassium (97 kg K/ha), nitrogen (57 kg N/ha) and Ca (13.5 kg Ca/ha) are potentially lost. This assumes these nutrient pools are either retained but immobilised or are volatilised (e.g. nitrogen).

Nutrient balance estimates

- Estimates of partial nutrient balances depended on whether rice stubbles are burnt after harvest or retained and incorporated back into the soil.
- Where stubbles were retained, balances for calcium, sulfur and magnesium were positive, but were negative for nitrogen, phosphorus and potassium. The phosphorus status of regional soils is marginal, but the potassium status is adequate.
- Stubble burning had a major impact on nutrient balance, and especially for potassium and nitrogen. The positive balances for sulfur and calcium (under stubble retention) became less positive, the negative balances for the other nutrients became more negative.

Implications for the rice industry

- Nutrient management in the rice region of southern New South Wales needs to be re-examined to ensure long-term maintenance of soil nutrient reserves.
- With the very high yields being achieved and the practice of burning large stubble masses, large quantities of all nutrients are being exported or potentially lost, and therefore soil nutrient reserves are being depleted. This is especially so for nitrogen, phosphorus and potassium.
- Inclusion of pasture or grain legumes in rice rotations is more sustainable than continuous rice rotations.
- Efficient strategies for supplying adequate phosphorus to rice rotations are required.
- Nutrients contained in the high levels of applied irrigation water, should be part of rice farm nutrient budgets.

Table 3.6 Nutrient balances (kg/ha) for rice grown using average industry inputs of irrigation water (13.3 ML/ha) and fertilisers to produce an average yield of 9.3 tonne grain/ha.

	Nitrogen	Phosphorus	Potassium	Sulfur	Calcium	Magnesium
Inputs						
Seed	1.5	0.4	0.5	0.1	0.04	0.16
Fertiliser	120	4.6	0	3.5	3.6	0
Irrigation water	4.6	0.7	3.9	18	24.5	15.3
Total inputs	**126.1**	**5.7**	**4.3**	**21.6**	**28.1**	**15.5**
Exports/losses						
Grain	93	23.1	29.1	7.7	2.2	9.7
Stubble burning	57	2.4	97	5.4	13.5	8
Nitrogen losses	42					
Balances						
Stubble retained	-9	-17.4	-24.7	13.9	25.9	5.7
Stubble burnt	-66	-19.8	-121.7	8.5	12.4	-2.3

DIRECTIONS FOR NUTRIENT MANAGEMENT

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.

Regular applications of superphosphate in the past, particularly in southern Australia, have improved the phosphorus, sulfur (and calcium) status of agricultural lands from their naturally infertile state. Nevertheless, attention now needs to focus on those regions where low or marginal soil nutrient status (e.g. soil phosphorus and potassium), and highly negative balances were broadly identified.

Nitrogen fertiliser applications to crops are now increasing (still augmented by large contributions from nitrogen fixing legumes). Continuing recent trends in nitrogenous fertiliser use must be balanced against increased risks of soil acidification and the potential loss of soil cations (in particular calcium, magnesium and potassium) leached with nitrate. Soil acidification potentially remains an insidious threat to production as Australia's acidifying farming systems and practices have been in place for many years in some regions. Soil acidification is closely linked with soil nutrient status and the management of nutrient supply and soil acidification should seek to be integrated.

Estimated farm-gate nutrient balance for nitrogen, phosphorus, sulfur, and calcium were predominantly neutral or moderately positive, suggesting that nutrient regimes are approaching near-optimal levels in many farming systems (providing nutrient losses are minimal), with the soils not being mined of their valuable nutrient reserves.

Some areas do also have highly negative balances (inputs < exports) causing nutrient depletion or highly positive (inputs > exports) nutrient balances exposing regional water bodies to potential risks of nutrient enrichment (see *Nutrient loads to Australian rivers and estuaries* section). The four industry-based, regional case studies had value in showing that improvements in nutrient use efficiency are still required in two key areas:

- Quantification of losses of specific nutrients by soil and crop husbandry (e.g. regional case studies on horticulture, dryland cropping and dairy); variable and often high removal of nutrients in harvested crops and stubbles (e.g. regional case study on rice); and the development of farming practices that improve nutrient use efficiency (e.g. case studies on horticulture and dryland cropping).
- The need for decision support systems on nutrient management remains a priority, so that optimal fertiliser use can be achieved. These systems should include estimates of nutrient loss—by soil fixation, gaseous loss, leaching or by overland flow in intensive farming systems (Moody et al. 1996, Nash & Murdock 1997, Fleming & Cox 1998, Ridley et al. 2001). We also need to identify areas at risk to off-farm leakage of nutrients (see *Nutrient loads to Australian rivers and estuaries* and Appendix 1).

In Queensland and regions such as the Wimmera and Riverina, the largely negative nutrient balances highlight the need for further regional investigation and interpretation. A negative balance, estimated consistently for these regions, indicates soil nutrient reserves are being depleted by current practices. In the longer term, such balances are not sustainable even though in the short term the soils may have adequate or high nutrient reserves. These balances will also become even more negative where substantial nutrient losses occur.

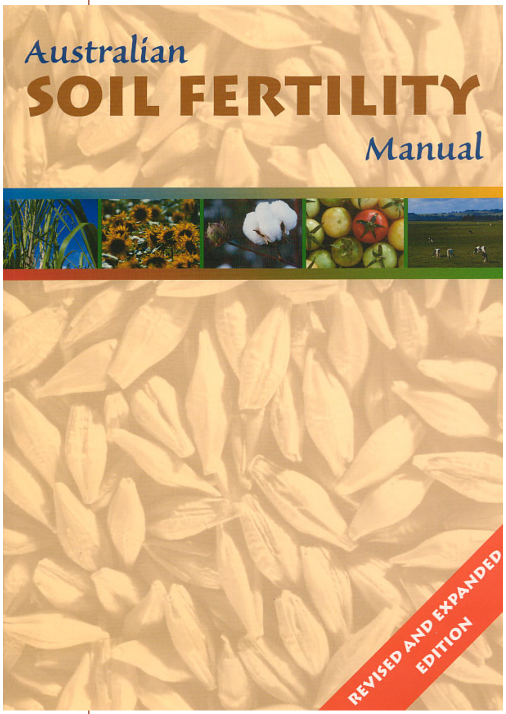
Changes in potassium balance between 1989–1996 in Western Australia, demonstrated the benefits that can accrue from detailed regional research and subsequent extension to farmers: again another positive outcome from the past decade.

It is also pleasing to note that the Fertilizer Industry Federation of Australia has published draft guidelines, based on the principles of ISO 14001, for individual commodity sectors to develop their own specific Nutrient Management Codes of Practice (see case study overleaf).

Advances by the Fertilizer Industry Federation of Australia

The mineral fertiliser industry in Australia is a $2 billion industry supplying over 5 million tonnes of fertiliser products to Australian farmers.

Fertilizer Industry Federation of Australia, Inc. is the industry association representing all of the manufacturers of mineral fertilisers and most importers. Fertilizer Industry Federation of Australia, Inc. members supply over 95% of the fertiliser used in Australia (excluding lime, gypsum and organic fertilisers).



Australian soil fertility manual

Fertilizer Industry Federation of Australia, Inc. commissioned market research among a range of industry stakeholders including farmers, fertiliser retailers and agents, farm advisers and consultants and found a need for better information on the proper use of fertilisers.

As a first step in filling this gap and in conjunction with CSIRO Publishing, the Fertilizer Industry Federation of Australia, Inc. published the *Australian Soil Fertility Manual*. The manual was released in 1999 and is being used as a basic reference for education and industry training and accreditation programs and for general use by consultants and farm managers. Over four thousand copies have been sold.

Cracking the nutrient code

The fertiliser industry has also recognised the importance of proper nutrient management at farm and catchment level to minimise losses of nutrient off farm. To assist individual industry sectors develop best management practices, the Fertilizer Industry Federation of Australia, Inc. released a draft set of guidelines—*Cracking the Nutrient Code*—for developing nutrient management codes of practice in May 2001. The guidelines are currently being evaluated by farmer organisations and various industry groups. Final guidelines will be published later in 2001.

The guidelines provide:

- a framework of overlying principles for nutrient management;
- describe a process for developing codes of practice; and
- provide technical information on nutrient management tools.

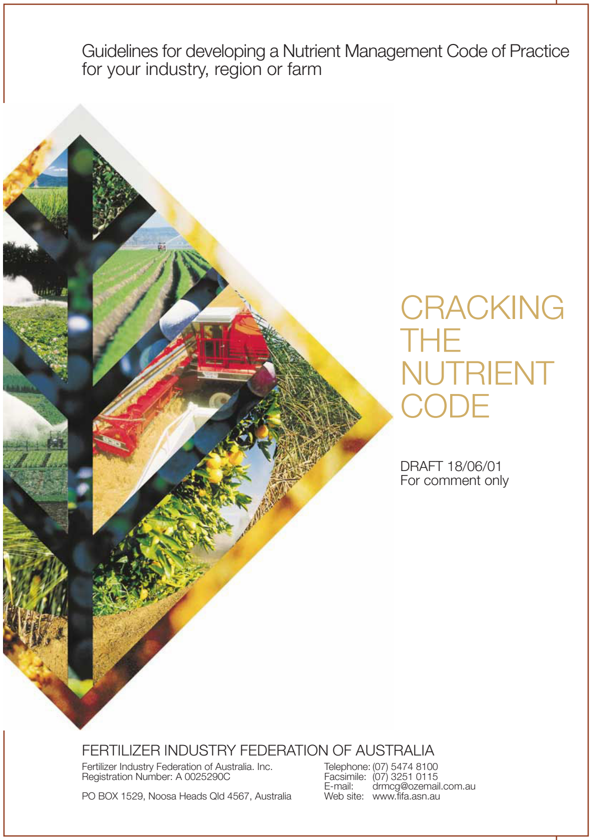
Input was sourced from specialists in environmental management systems, and the guidelines are developed on the basis of the principles of the International Management Systems Standard ISO 14001.

Investment in research and analytical laboratories

There has been a significant expansion in the adoption of soil testing by farmers over the past decade built on investments in expansion and upgrading of required laboratory and service delivery infrastructure.

Over the past decade Fertilizer Industry Federation of Australia, Inc. members have invested over $13.5 million in new laboratory facilities and in upgrading existing facilities.

To ensure that soil and plant analytical services are competently delivered, approximately 1800 company field staff, fertiliser agent and dealer staff have been trained by the industry in nutrient management. Approximately 600 have been accredited or judged to be competent to provide recommendations on fertiliser use based on soil and plant analysis.



Guidelines for developing a Nutrient Management Code of Practice
for your industry, region or farm

CRACKING
THE
NUTRIENT
CODE

DRAFT 18/06/01
For comment only

FERTILIZER INDUSTRY FEDERATION OF AUSTRALIA
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REFERENCES

ABARE 2000, *Australian commodities,* Australian Bureau of Agriculture and Resource Economics: Canberra.

Anderson G.C., Fillery I.R.P., Dunin F.X., Dolling P.J. & Asseng S. 1998, 'Nitrogen and water flows under pasture–wheat and lupin–wheat rotations in deep sands in Western Australia 2. Drainage and nitrate leaching', *Australian Journal of Agricultural Research* vol. 49, pp. 345–61.

Angus J.F. 2001, 'Nitrogen supply and demand in Australian agriculture,' *Australian Journal of Experimental Agriculture* vol. 41, pp. 277–88.

Bacon P. & Heenan D. 1987, 'Nitrogen budgets for intensive rice growing in Australia', in S. Banta (ed.) *Efficiency of nitrogen fertilizers for rice*, International Rice Research Institute. Los Banos, Phillipines.

Batten G.D., Blakeney A.B. & Ciavarella S. 2000, 'NIR for improved fertilizer predictions: update 2000', *IREC Farmers' Newsletter* (Large Area) vol. 154, pp. 36–3

Blakeney A.B., Batten G.D. & Ciavarella S. 1994, 'An interactive database for use with the rice tissue test service', in *Temperate Rice – achievements and potential*, E. Humphreys, E.A. Murray, W.S. Clampett & L.G. Lewin (eds), NSW Agriculture, Griffith.

Carey P. & Metherell A. 1999, 'Determining potassium requirements for pastoral agriculture: Review and recommendations', *AgResearch*, Lincoln New Zealand.

Daniells J.W. 1995, 'Results of a survey of research/development priorities and crop management practices in the north Queensland banana industry', DPI Bulletin QB95001, Department of Primary Industries, Brisbane.

Davies E.B., Hogg D.E. & Hopewell H.G. 1962, 'Extent of return of nutrient elements by dairy cattle: Possible leaching losses', *Proceedings of International Soil Science Conference*, Palmerston North, New Zealand.

Dillon P.J. 1988, *An evaluation of the sources of nitrate in groundwater near Mount Gambier, South Australia*, CSIRO Division Water Resources. Series Number 1, Canberra.

Eckard R.J., Chapman D.F., White R.E., Smith A., Chen D. & Durling P.A. 2001, 'Nitrogen balances in high rainfall, temperate dairy pastures of south-eastern Australia', in *Proceedings of XIX International Grasslands Congress*, 11–21 February, Sao Paulo Brazil.

Evans J., Chapman D., Aarons S., & Gourley C. 1998, 'The nitrogen economy of temperate dairy pastures', in *Dairy Research Foundation: Current Topics in Dairy Production V3*, J.M. Gooden & E.F. Annison (eds), University Printing Service Sydney.

Fleming N.K. & Cox J.W. 1998, 'Chemical losses off dairy catchments located on a texture–contrast soil: carbon, phosphorus, sulfur, and other chemicals', *Australian Journal of Soil Research* vol. 36, pp. 979–95.

Gourley C.J., Irvine J.N. & Sale P.W.G. 1998. 'Fertilizer decision making by dairy farmers', in *Technology and Training: Transforming Tomorrow. Proceedings of the 1998 Conference of the Fertilizer Industry Federation of Australia*, October 18–21 Perth WA, pp 66–69.

Greenhill N.B., Fung K.H., Peverill K.I. & Briner G.P. 1983, 'Nutrient content of rainwater in Victoria and its agricultural significance', *Search*, vol. 14, pp. 46–47.

Hamblin A. & Kyneur G. 1993, *Trends in wheat yields and soil fertility in Australia*, Australian Government Publishing Service, Canberra.

Hancock J. 1950, 'Studies in monozygotic cattle twins. IV: Uniformity trials: Grazing behaviour', *New Zealand Journal of Agricultural Research* vol. 3, pp. 377–383.

Hosking W.J. 1986, *Potassium for Victorian Pastures*, Department of Agriculture and Rural Affairs, Melbourne.

Knopke P., O'Donnell V., & Shepherd A. 2000, *Productivity growth in the Australian grains industry*, ABARE Research Report 2000.1, Canberra.

Ledgard S.F., Sprosen M.S. & Penno J.W. 2000 'Nitrogen cycling and losses in dairy farm systems varying in nitrogen fertiliser inputs', in *Soil 2000: New Horizons for a New Century*, Australian and New Zealand Second Joint Soils Conference Volume 2: Oral Papers, J.A. Adams & A.K. Metherell (eds), 3–8 December 2000, Lincoln University. New Zealand Society of Soil Science, pp. 173–174.

Ledgard S.F., Williams P.H., Broom F.D., Thorrold B.S., Wheeler D.M. & Willis V.J. 1999, 'OVERSEER TM – a nutrient budgeting model for pastoral farming, wheat potatoes, apples and kiwifruit', in *Best soil management practices for production*, L.D. Currie, M.J. Hedley, D.J. Horne & P. Loganathan (eds), Occasional report No. 12 FLRC, Massey University, Palmerston North, pp. 143–152.

Magdof F., Lanyon L. & Liebhardt B. 1997, 'Nutrient cycling, transformations and flows: implications for a more sustainable agriculture', *Advances in Agronomy* vol. 60, pp. 1–73.

Marr K.M, Batten G.D. & Blakeney A.B. 1995, 'Relationships between minerals in Australian brown rice', *Journal of Science and Food Agriculture* vol. 68, pp. 285–29.

Marr K.M., Batten G.D. & Lewin L.G. 1999, 'The effect of nitrogen fertilizer on yield, nitrogen and mineral elements in Australian brown rice', *Australian Journal of Experimental Agriculture* vol. 39, pp. 873–880.

Moody P.W., Reghenzani J.R., Armour J.D., Prove B.G. & McShane T.J. 1996, 'Nutrient balances and transport at farm scale—Johnstone River Catchment', in *Downstream effects of land use*, H.M. Hunter, A.G. Eyles & G.E. Rayment (eds), Department of Natural Resources, Queensland, Brisbane.

Nash D. & Murdoch C. 1997, 'Phosphorus in runoff from a fertile dairy pasture', *Australian Journal of Soil Research* vol. 35, pp. 419–29.

Pakrou N. & Dillon P.J. 2000, 'Key processes of the nitrogen cycle in irrigated and non-irrigated grazed pastures', *Plant and Soil* vol. 224, pp. 231–50.

Peoples M.B., Bowman A.M., Gault R.R., Herridge D.F., McCallum M.H., McCormick K.M., Norton R.M., Rochester I.J., Scammell G.J. & Schwenke G.D. 2000, 'Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia', *Plant & Soil* vol. 228, pp. 29–41.

Peverill K.I., Sparrow L.A. & Reuter D.J. 1999, *Soil Analysis: an interpretation manual*, CSIRO Publishing, Melbourne.

Phosphorus for Dairy Farms Project Team 1999, *Phosphorus for Dairy Farms Annual Report 1998/99*, Ellinbank Research Station.

Ridley A.M., White R.E., Helyar K.R., Morrison G.R., Heng L.K. & Fisher R. 2001, 'Nitrate leaching loss under annual and perennial pastures with and without lime on a duplex (texture contrast) soil in humid south-eastern Australia', *European Journal of Soil Science* vol. 52, pp. 237–52.

SCARM 1998, *Sustainable Agriculture: assessing Australia's recent performance*, CSIRO Publishing, Melbourne.

Simpson J., Muirhead W., Bowmer K., Cai G. & Freney J. 1988, 'Control of gaseous nitrogen losses from urea applied to flooded rice soils', *Fertilizer Research* vol. 18, pp. 31–47.

Uren N. 1991, *The management of soil organic matter for sustainable agriculture.* *Agricultural Science* vol. 4, pp. 45–7.

SUMMARY

Distribution and extent

- Surface and subsoil acidity exists in all Australian States. It has an estimated total area of eight to nine times that affected by dryland salinity.
- The largest areas of acid soils are in New South Wales, Western Australia, Victoria and Queensland.
- Approximately 50% of agricultural land (approximately 50 million hectares) have surface pH values less than or equal to 5.5 (or below optimum for extremely acid-sensitive agricultural plants and below the optimal level to prevent subsoil acidification).
- 12 to 24 million hectares is extremely to highly acidic with pH values less than or equal to 4.8 (below optimum for the acid-sensitive agricultural plants).
- Subsoil with a pH at or below 5.5 affect 23 million hectares of agricultural land.

Rates of acidification

- Rates of acidification vary appreciably across Australia's agricultural systems
- In the absence of remedial lime applications, from 29 to 60 million hectares are projected to reduce to pH 4.8 or lower within 10 years, and a further 14 to 39 million hectares will reduce to pH 5.5.

Projected lime requirement

- About 2 million tonnes of lime are applied to agricultural land each year. Lime use has increased in most States over the past decade.
- Approximately 12 and 66 million tonnes of lime are required to adjust existing acidic soils to a typical agricultural production pH of 4.8 and 5.5 respectively.
- Maintaining soil pH values at 4.8 and 5.5 requires ranges of 0.6 – 3.1 million tonnes and 2.4 – 12.3 million tonnes of lime each year respectively, to counter re-acidification at rates of 50 and 250 kg lime equivalent per ha each year respectively.
- Cost is a major deterrent to the wider use of lime in all States.
- Farmer awareness of soil acidification and its insidious consequences is by no means universal. Other farming practices (e.g. use of acid-tolerant plants) are being used where the cost of liming is prohibitive.

Off-site impacts

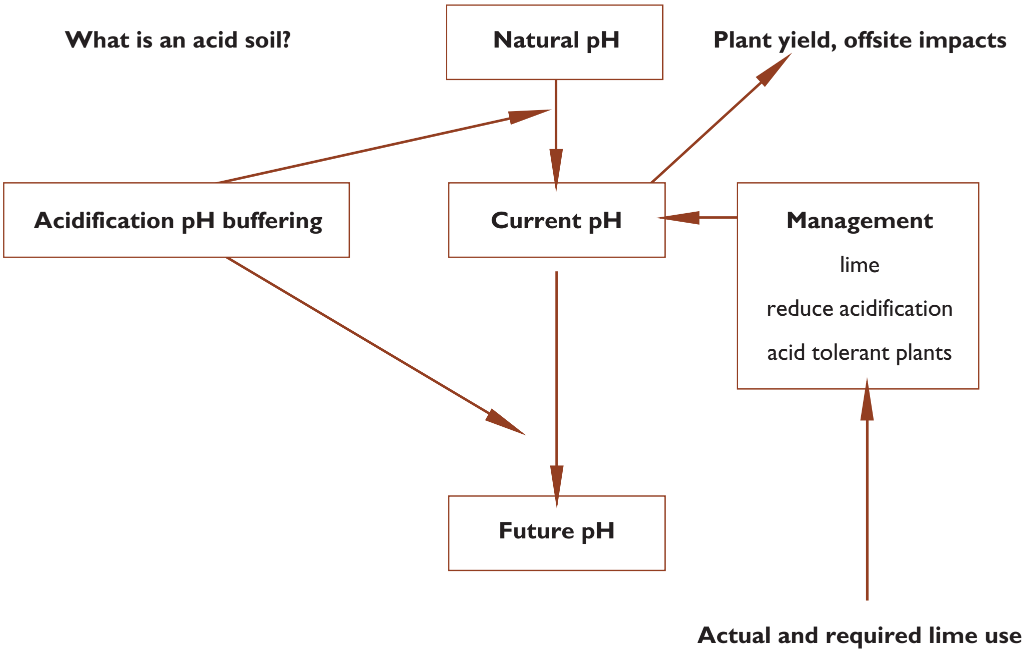
- Information linking soil acidity to off-site consequences is negligible. Many hypotheses exist and need to researched.

INTRODUCTION

Accelerated soil acidification is recognised globally as a serious soil degradation problem that is reducing agricultural production. The Audit commissioned a series of detailed assessments (Figure 4.1) on soil acidification including:

- mapping distribution and estimating extent of acidic soils in agricultural regions of Australia;
- predicting where soil acidity is likely to occur in the future;
- determining rates of soil acidification for regional farming systems;
- determining the pH buffering capacity of Australian soils, in order to assess where soils susceptible to acidification occur and how much lime is required to neutralise acidity;
- assessing plant yield penalties, financial benefits and costs associated with growing different plant species on a variety of soils with different acidity status and following the amelioration of acidity with lime applications;
- evaluating possible off-site risks of soil acidity; and
- summarising regional information on management options.

Figure 4.1 Soil acidification assessment approach.



ACIDIFICATION: THE PROCESS

Natural ecosystems

Soil acidification is a natural process. It begins when rocks are first colonised by algae and lichens. Acids (or protons) produced mainly from the carbon and nitrogen cycles begin to dissolve the rocks and soil minerals to form the parent soil. In natural ecosystems, soils gradually become more acidic with time so that older and more weathered soils are usually more acidic than younger soils.

In natural ecosystems, the amount of plant material and soil organic matter approaches equilibrium levels. Internal cycling of nutrients—especially nitrogen—is tightly controlled, and as a result, nitrogen losses as nitrate are minimal.

Nitrate leaching is considered to be a major cause of soil acidification in all ecosystems. Thus, in natural ecosystems, the inputs of acids are nearly balanced by neutralising processes, so that soils only become more acidic over many thousands of years.

Australia's soils are old and highly weathered. Some of them will be naturally more acidic than others. Natural acidity can also exist deeper down in the soil profile.

Agricultural systems

Soil acidification rates increase when land is developed for agriculture. *Induced acidification* (as distinct from natural acidification) involves changes to the nitrogen and carbon cycles, and the accumulation, depletion and transport of acids and bases (Helyar & Porter 1989). Induced acidification in soils arises from:

- leaching of soil nitrate—nitrate is very soluble in water and leaches below the root zone before the plant can take it up, leaving acidity in the soil; soil nitrate can come from legumes or nitrogen fertiliser. Application of ammonium fertilisers, which when converted to nitrate produce acidity;
- addition of organic acids;
- removal of alkalinity through removal (offtake) of crop and livestock products—removal of legume hay is a particularly acidifying practice (Table 4.1); and
- transfer of excreta to localised stock camps leaving surrounding land more acidic.

Soil acidification is an insidious soil process, developing slowly with subtle symptoms. If not corrected, the process can continue until irreparable damage occurs.

Table 4.1 The amount of lime needed to neutralise acidification caused by removal of alkalinity in agricultural produce.

Product	Yield	Lime requirement
Wheat	2 t/ha	18 kg/ha
Lupins	2 t/ha	40 kg/ha
Grass hay	5 t/ha	125 kg/ha
Clover hay	5 t/ha	200 kg/ha
Lucerne hay	5 t/ha	350 kg/ha
Wool*	5 kg/sheep	0.07 kg/sheep
Meat*	1 lamb	0.02 kg/lamb
Milk*	1000 litres	4 kg/1000 litres

* Additional acidification for the majority of the paddock occurs under set stocking with livestock. They consume pasture, which contains alkalinity and then deposit most of this alkalinity as dung and urine in areas where they camp, making most of the paddock more acid but the camps more alkaline.

MEASURING SOIL ACIDITY

Acidity is measured as pH: a logarithmic scale ranging from 0 to 14 (Figure 4.2). A neutral pH is seven, and each consecutive pH unit below seven (e.g. six) is ten times more acidic. Conversely, soils with pH values above seven become progressively more alkaline.

Traditionally, soil pH in Australia has been measured either in water (pH_w) or in 0.01M calcium chloride (pH_{Ca}). The latter test provides pH values about 0.8 – 0.9 pH unit lower than measurements in water (Figure 4.3), and has become the preferred test in most Australian States because the measurements are more stable. Unless otherwise stated, hereafter references to soil pH infers the pH_{Ca} test.

- *Acidic* soils are defined as those with a pH reading less than or equal to 5.5.
- *Moderately acidic* soils are those with pH values between 4.8 and 5.5.
- *Highly acidic* soils have pH values between pH 4.3 and 4.8.
- *Extremely acidic* soils have pH values less than 4.3.

Figure 4.2 Soil pH range (pH measured in 0.1M $CaCl_2$).

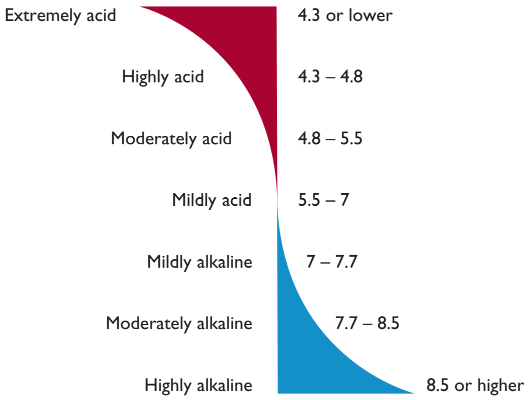
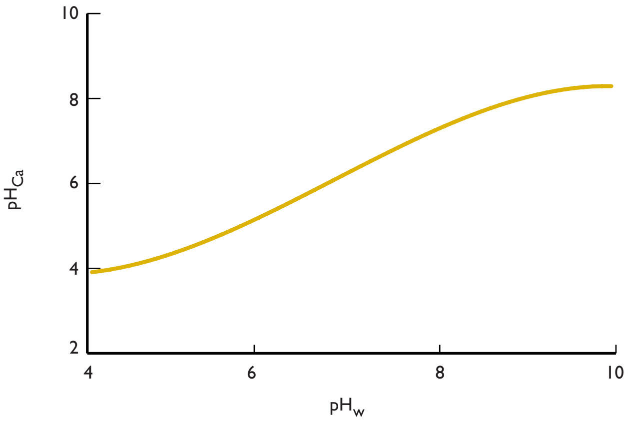


Figure 4.3 Relationship between soil pH $_W$ and pH $_{Ca}$ (Ahern et al. 1995).



ASSESSING DISTRIBUTION OF ACIDIC SOILS

Two approaches were used to report on the distribution of acidic soils. They give independent estimates of soil pH (except for South Australia), but should only be used as guides because of potential errors are associated with each method.

Commercial soil testing

- 636 000 surface soil pH values were collected from 12 private and public sector agencies operating commercial soil testing services for farmers. These data (covering 1990 to 1999) for the surface soil depth (range 0–15 cm, but dominated by 0–10cm depths and 0–10cm in Western Australia) were merged, allocated to the nearest town and areas (polygons) were drawn around each town. The exceptions were Western Australia, (where the data were allocated to 20 km by 20 km grids) and South Australia, (where about 50% of samples were referenced to property centroids). Samples reporting pH measured in water from Queensland and northern New South Wales were converted to pH in calcium chloride using the Ahern et al. (1995) equation.

  The data were allocated to pH classes (see below) and the proportion of each class determined in each polygon. From this information, statistics on areas and maps were generated showing the spatial distribution of soil pH in the agricultural area, which was not limited to the intensive land use zone. The exception was again Western Australia where there was no commercial pH data for 2.9 million hectares of agricultural land.

  Since samples were collected from non-random locations, errors may result from particular soil types being sampled and biasing the polygon data set. Some polygons had limited number of points (< 10 values) and therefore there is a greater risk of inaccuracy.

Australian Soil Resources Information System

- These data came from CSIRO and State agency soil survey data sets. They cover soil samples from both agricultural and uncleared lands, and for surface and subsoils.

  A modelling approach was used to:

  - generate models for soil pH, based on the soil point data;
  - extend these models to predict the pH for 250 m by 250 m cells, based on soil type data, topographic variables and climate surfaces; and
  - assess the precision and accuracy of the models.

  The models satisfied statistical tests in most States (with the exception of South Australia) and a new model was derived using South Australian commercial pH data. Although the models allowed pH to be derived at a finer scale of resolution than by using commercial data, point data from government databases is not as contemporary as the commercial pH data.

  From the modelled pH information, statistics on areas and maps were generated showing the spatial distribution of soil pH in catchment containing areas of intensive land use.

DISTRIBUTION AND EXTENT OF ACIDIC SOILS IN AUSTRALIA

Surface soils

Maps generated from commercial farm soil testing data collected over the past decade (Figure 4.4) and State/Territory agency land resource assessment programs (Australian Soil Resources Information System) (Figures 4.5, 4.6) were broadly consistent:

- Both indicate considerable spatial variation in surface soil pH within Australia's agricultural zone.
- Both sources of pH information show that there are major areas of acidic soils (pH less than or equal to 5.5) in all States (Table 4.2)

Ranges quoted relate to the estimates from commercial agencies and Australian Soil Resources Information System.

Acidic soils are more prevalent where annual rainfall exceeds 500 mm, and are most concentrated in a broad band extending from the central Tablelands of New South Wales through central Victoria into south-eastern South Australia. Major acidic areas also occur in the agricultural zone of Western Australia.

Within the agricultural areas of Australia (Table 5.2), it was estimated that between 11 and 21 million hectares of agricultural land had strongly acidic topsoils (pH 4.3 – 4.8), and from 1 to 3 million hectares were extremely acidic (pH less than 4.3). A much larger area of land (25 to 37 million hectares) was estimated to have moderately acidic topsoils (pH 4.8 – 5.5).

- The largest area of strongly acidic soils (pH 4.3 – 4.8) existed in New South Wales (5 to 7 million hectares), Victoria (4 to 5 million hectares) and Western Australia (1 to 7 million hectares).
- The largest area of moderately acidic soils (pH 4.8 – 5.5) occurred in Western Australia (7 to 19 million hectares) and New South Wales (11 to 13 million hectares) and to a lesser extent Victoria (2 to 3 million hectares).

Table 4.2 National and State areas (million hectares) of surface soil (0–10 cm) pH (measured in calcium chloride) based on information from Australian Soil Resources Information System (first number) and commercial laboratories (second number).

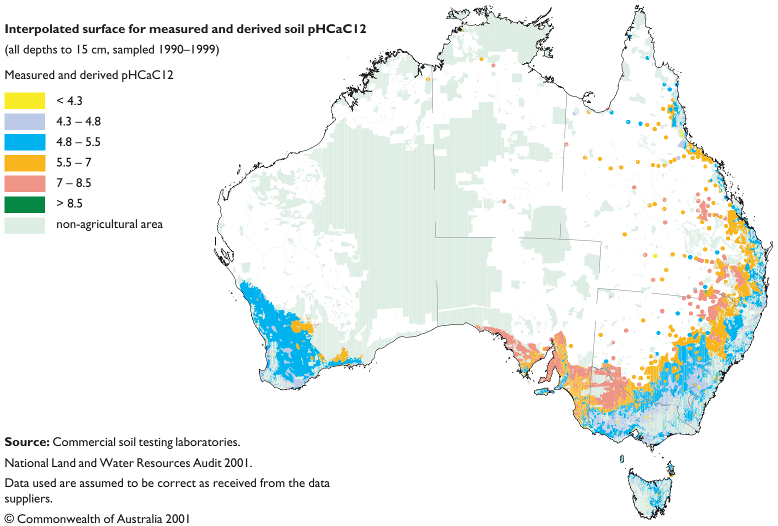
	< 4.3	4.3[a] – 4.8[a]	4.8 – 5.5[a]	5.5 – 7.0[a] (million hectares)	7.0 – 8.5[a]	> 8.5	Total[c]
New South Wales	0.2 – 1.1	4.8 – 7.1	12.7 – 10.6	18.5 – 10.9	1.5 – 7.9	0 – 0.0[b]	37.6 – 37.8
Queensland	~ 0.3	0.6 – 1.0	1.5 – 1.8	7.4 – 3.7	0.8 – 4.3	0	10.5 – 11.1
South Australia	≤ 0	0.2 – 0.5	0.8 – 1.4	4.3 – 3.6	6.7	0.0[b]	11.9 – 12.2
Tasmania	~ 0.1	0.6 – 0.5	1.0 – 0.9	0.0[b] – 0.3	0.0[b]	0	1.6 – 1.8
Victoria	0.4 – 1.0	4.1 – 4.5	2.0 – 3.1	4.8 – 2.0	2.9 – 3.5	0 – 0.0[b]	14.1 – 14.2
Western Australia	0.1 – 0.7	1.0 – 7.5	7.4 – 18.9	1.4 – 2.4	0.0[b] – 1.1	0	21.4 – 19.2
Australia[c]	**1.1 – 3.3**	**11.3 – 21.2**	**36.8 – 25.2**	**36.3 – 22.9**	**11.8 – 23.5**	**0.0[b] – 0.1**	**97.3 – 96.2**

[a] Inclusive

[b] Numbers rounded to 0.0 vary from 0.01 – 0.03.

[c] Total values may be slightly different to adding up the values in the table because of rounding errors.

Figure 4.4 Interpolated topsoil soil pH (1990–1999).



Source: Commercial soil testing laboratories.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

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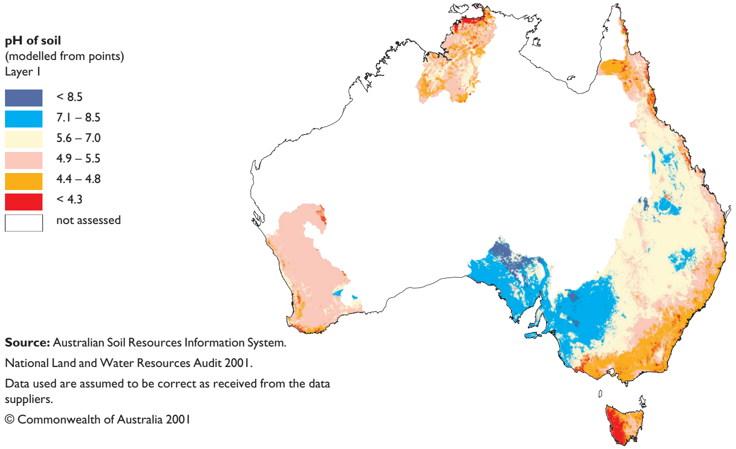
Figure 4.5: Modelled topsoil pH.



Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

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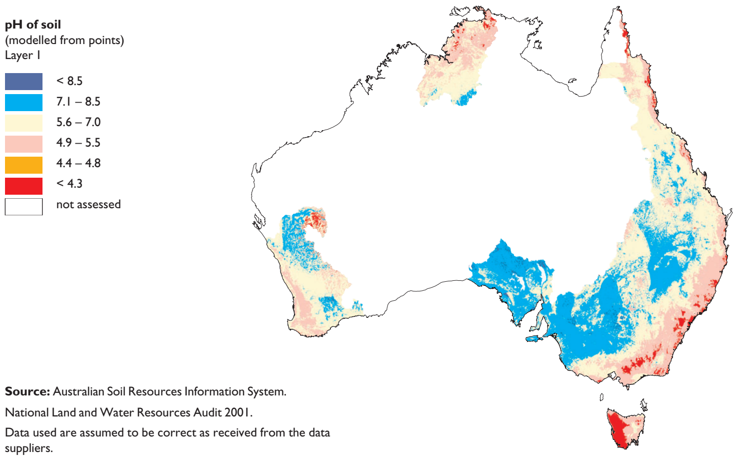
Figure 4.6 Modelled subsoil pH.



Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

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Subsoils

Modelled data from the Australian Soil Resources Information System were used to map the distribution of acidic pH classes pH 4.8 and 5.5 in both the surface and subsoil layers (Figures 4.7, 4.8).

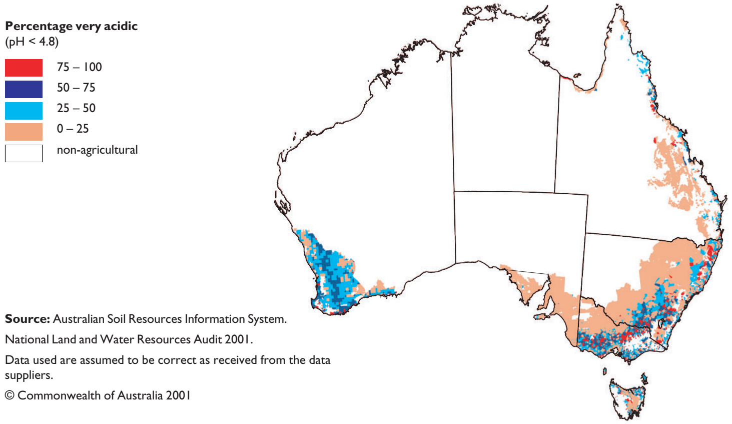
Large regions of land in all States have moderately acidic soil (pH below 5.5) in both the surface and subsoil (Figure 4.8), and particularly in New South Wales, Western Australia, Victoria and Queensland. Regions with strongly acidic surface and subsoil pH values (< pH 4.8) were far less extensive (Figure 4.7).

Nationally, the extent of subsoil acidity was estimated to be large (Table 4.3):

- about 23.1 million hectares of land had subsoil acidity grading from extreme to moderate severity (pH less than or equal to 5.5);
- 21.7 million hectares had pH less than or equal to 5.5 in both the surface and subsoil layers;
- 5.3 million hectares had subsoils with pH < 4.8 (strongly acidic), and 0.8 million hectares had a pH < 4.3 (extremely acidic);
- 0.2 million hectares had pH values < 4.3 (extremely acidic) in both soil layers;
- 3.8 million hectares had soil pH < 4.8 (strongly acidic) in both soil layers; and
- 0.7 million hectares had pH <4.3 in the subsoil and pH < 4.8 in the surface.

At a State level, New South Wales has the largest estimated area of subsoil acidity (3.1 million hectares below pH 4.8 and 8.6 million hectares between pH 4.8 and 5.5 (Table 4.4), followed by Western Australia (0.2 and 4.8 million hectares respectively) and Victoria (0.6 and 2.5 million hectares respectively).

Figure 4.7 Distribution of topsoil and subsoil acidity within Australia's agricultural zone.

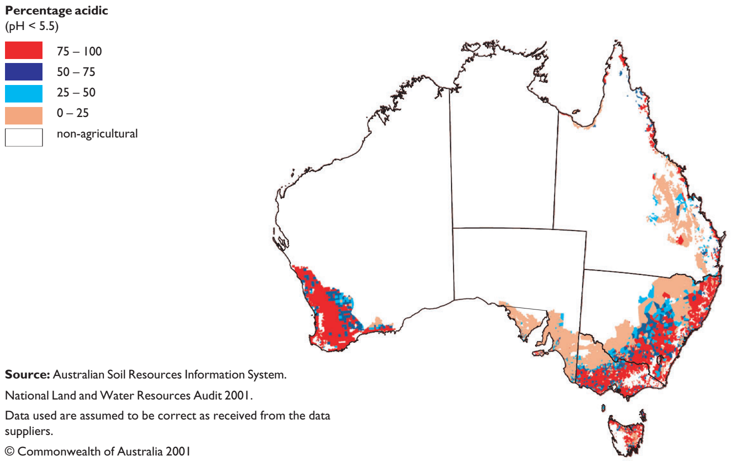


Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 4.8 Distribution of topsoil and subsoil acidity within Australia's agricultural zone.



Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Table 4.3 National area (million hectares) of surface soil (0–10 cm) and subsoil (30–40 cm) pH_{Ca} based on information from the Australian Soil Resources Information System.

	pH	Surface soil						Total[c]
		⩽ 4.3	4.3 – 4.8[a]	4.81 – 5.5[a]	5.51 – 7.0[a]	7.0 – 8.5[a]	> 8.5	
		(million hectares)						
	⩽ 4.3	0.2	0.5	0.1	0.0[b]	0	0	0.8
	4.3 – 4.8[a]	0.2	2.9	1.3	0.0[b]	0.0[b]	0	4.5
Subsoil	4.81 – 5.5[a]	0.4	5.1	10.9	1.3	0.1	0	17.8
	5.51 – 7.0[a]	0.3	2.6	21.3	18.4	2.3	0	45.0
	7.0 – 8.5[a]	0.0[b]	0.2	2.9	16.2	9.2	0	28.6
	> 8.5	0.0[b]	0	0.2	0.3	0.3	0	0.7
	Total[c]	**1.1**	**11.3**	**36.8**	**36.3**	**11.8**	**0.0[b]**	**97.3**

a Inclusive

b Numbers rounded to 0.0 vary from 0.01 – 0.04.

c Total values may be slightly different to adding up the values in the table because of rounding errors.

Table 4.4 National and State areas (million hectares) of surface soil pH_{Ca} with a subsoil pH_{Ca} of < 4.8 and 4.8 – 5.5 based on information from Australian Soil Resource Information System.

	Subsoil pH = 4.8				**Subsoil pH = 4.8 – 5.5[a]**			
	Surface pH				Surface pH			
	⩽ 4.8	4.8 – 5.5[a]	> 5.5	Total[c]	⩽ 4.8	4.8 – 5.5[a]	> 5.5	Total[c]
	(million hectares)				(million hectares)			
New South Wales	2.2	0.9	0.0[b]	3.1	2.2	5.5	0.9	8.6
Queensland	0.6	0.3	0.0[b]	0.9	0.3	0.5	0.1	0.9
South Australia	0.0[b]	0.0[b]	0.0[b]	0.0[b]	0.0[b]	0.0[b]	0.1	0.1
Tasmania	0.3	0.1	0	0.5	0.3	0.5	0.0[b]	0.8
Victoria	0.6	0.0	0.0[b]	0.6	2.0	0.4	0.1	2.5
Western Australia	0.1	0.1	0.0[b]	0.2	0.7	4.0	0.2	4.8
Australia[c]	**3.8**	**1.5**	**0.1**	**5.4**	**5.5**	**10.9**	**1.4**	**17.8**

a Inclusive

b Numbers rounded to 0.0 vary from 0.01 – 0.03.

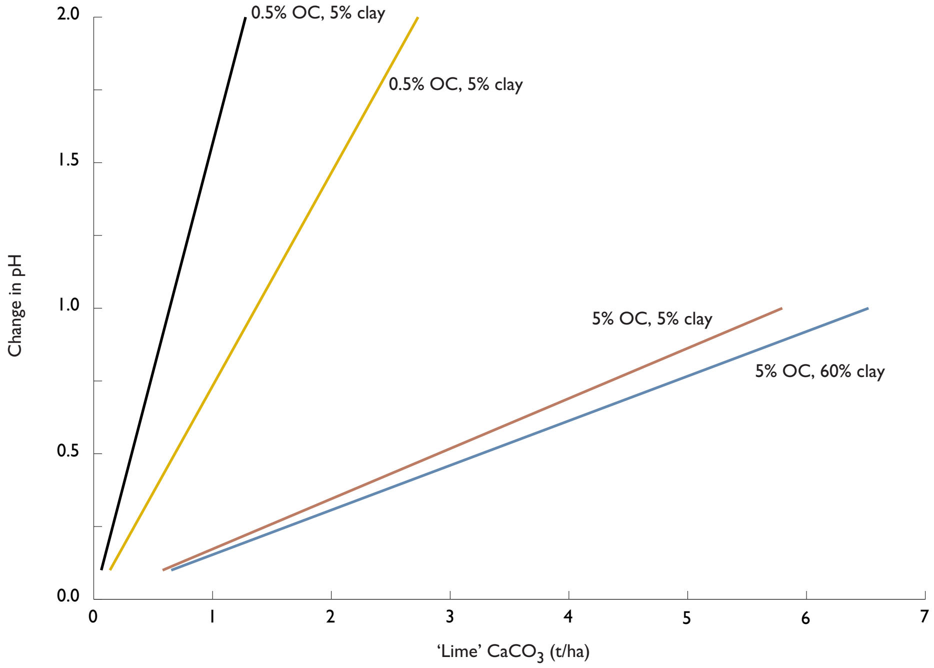
c Total values may be slightly different to adding up the values in the table because of rounding errors.

CAPACITY OF AUSTRALIAN SOILS TO RESIST pH CHANGE

Soils have an intrinsic ability to resist pH change—either a decrease from an acid input (acidification) or an increase from the application of lime (lime requirement). This is known as the pH buffering capacity and is determined by a chemical test.

Organic matter is the major determining factor influencing pH buffering; clay content is the next important factor. A higher organic matter or clay content will result in a higher pH buffering capacity (Figure 4.9). Estimates of pH buffering capacity are important for providing advice on levels of lime application required to correct soil acidity. Units are usually expressed as tonnes of lime per hectare per pH unit change.

Figure 4.9 Predicted relationships between the quantities of lime required to change soil pH (estimate of pH buffering capacity) on soils with varying soil organic carbon and clay contents.



Estimating pH buffering capacity

Review and testing of published relationships between pH buffering capacity and soil properties to determine the most appropriate test was carried out. The best relationship (correlation or r^2 of 0.7 – 0.9) for a wide range of surface soils was by Aitken et al. (1990):

$$\text{pH BC} = [0.955 \text{ OC\%} + 0.011 \text{ Clay\%}] \times 1.2$$

A visual representation of this relationship is shown in Figure 4.9. The relationship is expressed as tonnes of lime required to change the pH by one unit per hectare assuming a surface soil bulk density of 1200 kg/m^3.

This relationship was poor for wet tropical soils with variable charge characteristics and predicted pH buffering capacity on these soil types will have greater risk of error. Approximately half the lime applied to these soils is used to generate increased cation exchange capacity rather than in raising soil pH. Data for more appropriate tests for these soils were not available.

For subsoils

Australian literature contains little evidence on pH buffering capacity relationships for subsoil. Functions that rely on soil organic carbon alone as a variable would provide overestimates. A relationship (Noble et al. 1997) that relies less on the organic carbon compared to the relationship for the surface soil was used for the subsoils (30 – 40 cm):

$$\text{pHBC} = [12.79 - 0.19 \text{ Clay\%} - 0.7 \text{ OC\%} - 0.03 \text{ Silt\%} + 0.74 \text{ Silt\%} \times \text{OC\%}] \times 0.06$$

pH BC (measured as $t\ CaCO_3/ha/pH$) refers to tonnes of lime per hectare per pH unit; and

OC% is the organic carbon percent

Clay% is the clay percent

Silt% is the silt percent

It is anticipated that these functions for pH buffering capacity, and possibly other functions listed in the Audit *Soil Acidity Report* (Dolling et al. 2001), will be used by agricultural service agencies to better estimate lime requirements for acidic soils identified in Australia.

Maps of pH buffering capacity based on these relationships were generated at a nominal resolution of 250 m grid cells from the modelled organic carbon, clay and silt data in the Australian Soil Resources Information System.

pH buffering capacity variations in Australian soils

- 27 million hectares (74% of the 37 million hectares of *moderately acidic* surface soils) require very low to low amounts of lime (less than or equal to 1.5 tonnes lime per hectare) to increase the surface soil pH by one unit (Table 4.5, Figure 4.10). In highly acidic soils, the area of soils requiring very low to low amounts of lime to increase the surface soil pH by one unit was 4 million hectares (or 33% of the 11 million hectares of the highly acidic soils; Table 4.5, Figure 4.10).
- 91% of the 19 million hectares of *moderately acidic* surface soils in Western Australia require very low to low amounts of lime (less than or equal to 1.5 tonnes lime per hectare) to increase the pH by one unit (Table 4.5, Figure 4.10). In comparison, greater amounts of lime are estimated to be required to increase the pH in New South Wales with 66% of the 13 million hectares requiring very low to low amounts of lime to increase the pH by one unit. In the other States, the pH buffering was generally low to moderate (0.5 – 2.5 tonnes lime per hectare per pH unit) (Table 4.6, Figure 4.10).
- 84% of the 5 million hectares of *strongly acidic* soils in New South Wales require low to moderate amounts of lime (0.5 – 2.5 tonnes lime per hectare per pH unit) to increase the pH by one unit (Table 4.6). In Victoria, greater amounts of lime are required, with 89% of the 4 million hectares requiring moderate to high amounts of lime (>1.5 or >2.5 tonnes lime per hectare) to increase the pH by one unit (Table 4.5, Figure 4.10).

Table 4.5 Estimated area (million hectares) of agricultural land in Australia having topsoils with very low to high pH buffering capacity.

Estimated area (million hectares)	**Tonnes lime per hectare to raise one pH unit**			
Topsoil pH	⩽ 0.5	0.5 – 1.5[a]	1.5 – 2.5[a]	> 2.5
⩽ 4.3[d]	0.1	0.2	0.3	0.5
4.3 – 4.8[a]	0.3	3.4	3.6	3.9
4.8 – 5.5[a]	9.5	17.9	6.0	3.1
5.5 – 7.0[a]	6.8	21.2	6.3	1.8
7.0 – 8.5[ae]	5.4	4.8	1.8	0.4
> 8.5[e]	0.0[b]	0.0	0.0	0.0
Total[c]	**22.1**	**47.5**	**18.0**	**9.6**

[a] Inclusive

[b] Numbers rounded to 0.0 vary from 0.01 – 0.03.

[c] Total values may be slightly different to adding up the values in the table because of rounding errors.

[d] Underestimates the amount of lime required, because the breakdown of clay minerals and the increase of aluminium, which increases the amount of lime required, was not taken into account.

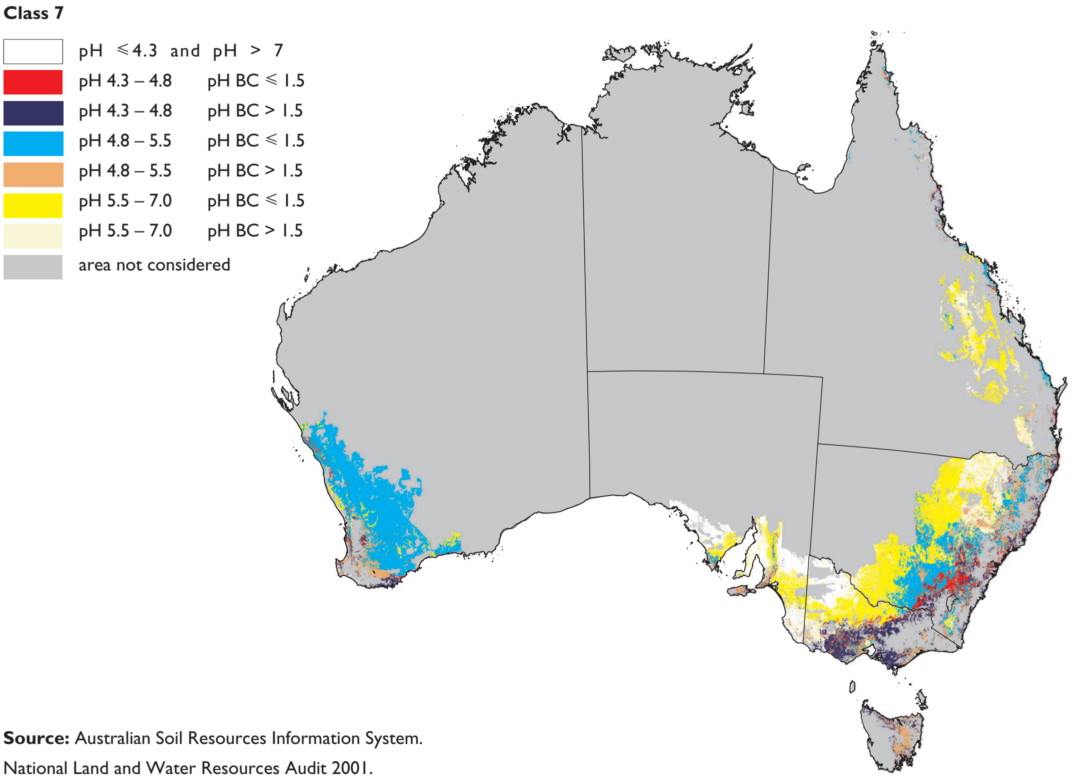
[e] Underestimates the amount of lime required, because the effect of the calcium carbonate (lime) naturally occurring in these soils on their pH buffering capacity could not be estimated.

The pH buffering capacity of soil also influences the time taken for soil to decrease to a pH value which would impair plant growth. In the context of acidification, the pH buffering capacity is expressed in terms of the amount of lime required to neutralise the acid inputs.

- Most (74–77%) strongly and moderately acidic surface soils in Australia have a very low to low pH buffering capacity (below 1.5 tonnes of lime per hectare per one pH unit) (Table 4.5) and are therefore at risk to acidifying more rapidly, and especially where rates of acid addition are high.

Data on pH buffering capacity were also used to estimate and map lime requirement strategies and determine the time taken to become acidic, either pH 4.8 or 5.5.

Figure 4.10 Distribution of topsoil pH buffering capacity in Australia's agricultural regions.



Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Table 4.6 Estimated area (million hectares) of agricultural land by State having topsoils with very low to high pH buffering capacity.

Surface soil pH	State	Tonnes lime per hectare to raise one pH unit				Total[c]
		< 0.5 Very low	0.5 – 1.5[a] Low	1.5 – 2.5[a] Moderate	> 2.5 High	
		(million hectares)				
⩽ 4.3	Australia[d]	0.1	0.2	0.3	0.5	1.1
4.3 – 4.8[a]	New South Wales	0.1	2.4	1.6	0.7	4.8
	Queensland	0.1	0.3	0.2	0.1	0.6
	South Australia	0.0[b]	0.1	0.1	0.1	0.2
	Tasmania	0	0	0.1	0.5	0.6
	Victoria	0	0.4	1.4	2.3	4.1
	Western Australia	0.2	0.2	0.3	0.3	1.0
	Australia[c]	0.3	3.4	3.7	4.0	11.3
4.8 – 5.5[a]	New South Wales	0.9	7.5	3.0	1.3	12.7
	Queensland	0.2	0.7	0.4	0.2	1.5
	South Australia	0.0[b]	0.3	0.3	0.2	0.8
	Tasmania	0	0	0.3	0.7	1.0
	Victoria	0.0[b]	0.5	1.1	0.5	2.0
	Western Australia	8.3	8.9	1.2	0.4	18.9
	Australia[c]	9.5	17.9	6.2	3.2	36.8
5.5 – 7.0[a]	New South Wales	3.3	10.9	3.4	0.9	18.5
	Queensland	1.1	4.2	1.7	0.3	7.4
	South Australia	1.1	2.4	0.6	0.1	4.3
	Tasmania	0	0	0	0	0.0[b]
	Victoria	0.7	3.1	0.6	0.4	4.8
	Western Australia	0.6	0.6	0.1	0.1	1.4
	Australia[c]	6.8	21.2	6.4	1.7	36.3
> 7.0	Australia[e]	5.4	4.8	1.9	0.4	12.5

[a] Inclusive

[b] Numbers rounded to 0.0 vary from 0.01 – 0.03.

[c] Total values may be slightly different to adding up the values in the table because of rounding errors.

[d] Underestimates the amount of lime required, because the breakdown of clay minerals and the increase of aluminium, which increases the amount of lime required, was not taken into account.

[e] Underestimates the amount of lime required, because the effect of the calcium carbonate (lime) naturally occurring in these soils on their pH buffering capacity could not be estimated.

Annual rates of acidification

Annual rates of acid addition vary with the type of farming system and seasonal conditions (seasonal conditions affect the extent of nitrate leaching, a major factor in soil acidification). Rates of acidification are conventionally expressed as *lime needed to neutralise the acid load generated each year* (kg lime/ha/year).

Annual acidification rates estimated between different farming systems in tropical, temperate and Mediterranean regions across Australia (Table 4.7) are mostly positive (i.e. the farming system requires an input of lime to maintain soil pH). Where acidification values are negative, no lime is required. The data have been summarised by agro-ecological regions, farming system and commodity classification.

- Estimates of acidification rates vary from an alkalising farming system of tobacco production (-260 kg lime/ha/yr) to strongly acidifying farming systems such as banana production (2000 kg lime/ha/yr) (see case study). Rates are more commonly in the range 50 to 250 kg lime/ha/year.

  The tobacco industry uses nitrate fertilisers, which add alkalinity to the soil. By comparison, the banana industry is located in a high leaching environment and use high rates of nitrogenous fertilisers. Consequently, the industry has a high rate of nitrate leaching, which causes acidification. However changes in fertiliser types and management can significantly alter the acid addition rate.
- Acidification rates can also be high on sandy soils that are subject to extreme leaching, particularly under wheat due to the application of ammonium fertilisers and rapid leaching of nitrate during early crop development.
- Rates of nitrate leaching are generally lower under perennial pastures than under annual pastures (e.g. Ridley et al. 2001).
- Crops are generally more acidifying than pastures, and continuous legumes and pasture cut for hay can have very high acidification rates (Tables 4.7, 4.8).

Table 4.7 Published acid addition rates (annual acidification rates, kilogram lime per hectare per year) for Australian agricultural and pastoral systems.

Agro-ecological region	Farming system	Commodity classification	Annual acidification rates (mean)	Annual acidification rates (range)	Data quality[a]
NW wet/dry tropics	Stylosanthes spp. based pastures	Grazed pasture	60	25–90	M1
NE wet/dry tropics	Stylosanthes spp. based pastures	Grazed pasture	60	0–175	H
NE wet/dry tropics	Stylosanthes seed production	Seed production	530		M2
NE wet/dry tropics	Tobacco monoculture	Other non-cereal crops	(–)120[b]	(–)260[b] –25	H
Wet tropical coast	Grass & legume pasture; grass + N[c]	Pasture cut for hay	320	50–550	H
Wet tropical coast and Wet subtropical coast	Sugar cane monoculture	Sugar cane	170	140–235	H
Wet tropical coast	Banana monoculture	Plantation fruit	1710	1400–2000	H
Subtropical slopes and plains	Leucaena	Agroforestry[d]	50		M2
Subtropical slopes and plains	Stylosanthes spp. based pastures	Grazed pasture	55		M2
Subtropical slopes and plains	Grape monoculture	Grapes	95	65–125	M1
Wet subtropical coast	White clover/paspalum/carpet grass	Grazed pasture	125	60–180	M1
Wet temperate coasts	Continuous grazing	Grazed pasture[e]	55	12.5–132	H
Wet temperate coasts	Continuous grazing with feed supplements (intensive dairy)	Grazed pasture[e]	25	(–)10.5[b] –95	H
Wet temperate coasts	Regular hay cutting; med to high intensty grazing	Pasture cut for hay	85	5–145	H
Temperate highlands	Eucalypt forest	Agroforestry[d]	45		M2
Temperate highlands	Sub clover/annual grasses; sub clover/perennial grasses	Grazed pasture	120	40–220	H
Temperate highlands	Continuous wheat ± N[c]	Cereals excluding rice	105	45–230	H
Temperate highlands	Continuous lupin	Legumes	625		M2
Temperate slopes and plains	Continuous pasture; dryland lucerne	Grazed pasture	50	25–80	H
Temperate slopes and plains	Continuous wheat (fertilised with N and P)	Cereals excluding rice	80	20–145	H
Temperate slopes and plains	Continuous lupin	Legumes	72.5		M1
Temperate slopes and plains	Canola	Oil seeds	128		M1

[a] The data quality was assessed as either; high (H) data obtained over more than 3 sites using clearly defined methodology, medium 1 (M1) data obtained over 2–3 sites using clearly defined methodology, medium 2 (M2) data obtained from 1 site using clearly defined methodology.

[b] The negative value (–) indicates lime is applied to soil rather than lime being required to neutralise the acidity.

[c] +N indicates nitrogen fertiliser was applied, –N indicates no applied nitrogen.

[d] Data on annual acidification rates under agroforestry are very limited. Some trees (e.g.. white cedar) are known to cause net alkalisation of the surface soil. The annual acidification rates for agroforestry should therefore be treated with caution, as it will depend on the species grown.

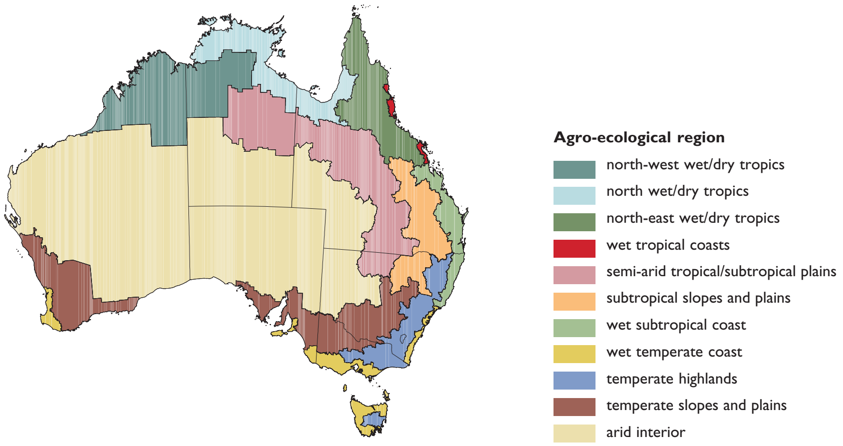
[e] It is important to distinguish between grazed pasture, and grazed pasture with feed supplements, as the latter can cause net alkalisation.

Table 4.8 Published acid addition rates (annual acidification rates, kilograms of lime per hectare per year) for different cropping and pasture rotations.

Agro-ecological region	Farming system	Commodity classification	Annual acidification rates (mean)	Annual acidification rates (range)	Data quality[a]
NE wet/dry tropics	Summer crop – winter fallow	Summer crop rotations	75	40–150	H
NE wet/dry tropics	Crop – pasture rotation	Summer crop/pasture rotation	75		M1
Subtropical slopes and plains	Summer crop – winter fallow	Summer crop rotations	125	70–175	M1
Wet temperate coasts	Crop – pasture rotation	Winter crop/pasture rotation (wheat, barley, canola, peas, beans)	110		H
Temperate highlands	Wheat – pasture, – N [b]	Wheat/pasture rotation	115	62.5–195	H
Temperate highlands	Wheat – lupin	Wheat/lupin rotation	140	70–205	H
Temperate slopes and plains	Pasture – wheat	Wheat/pasture rotation	20	10–40	H
Temperate slopes and plains	Wheat – lupin, pasture–wheat–lupin	Wheat/lupin rotation	20	10–30	H
Temperate slopes and plains	Crop – pasture rotation	Winter crop/pasture rotation. (wheat, barley, canola, peas, beans)	110	25–345	H
Temperate slopes and plains	Continuous crop	Continuous winter crop (wheat, barley, canola, peas, beans)	220	170–320	H
Temperate slopes and plains	Rice – wheat – pasture (irrigated)	Irrigated rice/wheat/ pasture rotations	470	395–520	H

a The data quality was assessed as either; high (H) data obtained from more than 3 sites using clearly defined methodology, medium 1 (M1) data obtained over 2–3 sites using clearly defined methodology.

b –N indicates no nitrogen fertiliser was applied.



Predictions for future soil acidification risk

Estimates were made of how long it would take, *in the absence of lime applications,* for agricultural surface soils to decrease to pH 4.8 or 5.5.

Results from this analysis are an early warning signal to land managers that soil acidity may be a problem.

The areas of, and times for Australia's soils to reach either pH 4.8 or 5.5 primarily depend on the rate of acid addition (Figures 4.11 and 4.12). Predicted areas that will become highly acidic (pH 4.8) within 5 or 10 years are substantially greater than those predicted to become moderately acidic (pH 5.5, e.g. compare Figures 4.11a with 4.12a and Figures 4.11b with 4.12b). This is related to the large areas of agricultural land in Australia that are already moderately acidic.

Nationally, almost 29–60 million hectares (minimum–maximum acid addition rates) are projected to reach pH 4.8 within 10 years, with Western Australia (14 to 20 million hectares) and New South Wales (8–22 million hectares) being the States most at risk (Table 4.9). The model also predicted that from 18% (minimum acid addition rates) to 44% (maximum acid addition rates) of the total land affected will reach pH 4.8 within five years.

By comparison, 14–39 million hectares (minimum–maximum acid addition rates) were predicted to reach pH 5.5 within 10 years and from 6–25 million hectares within five years (Table 4.9).

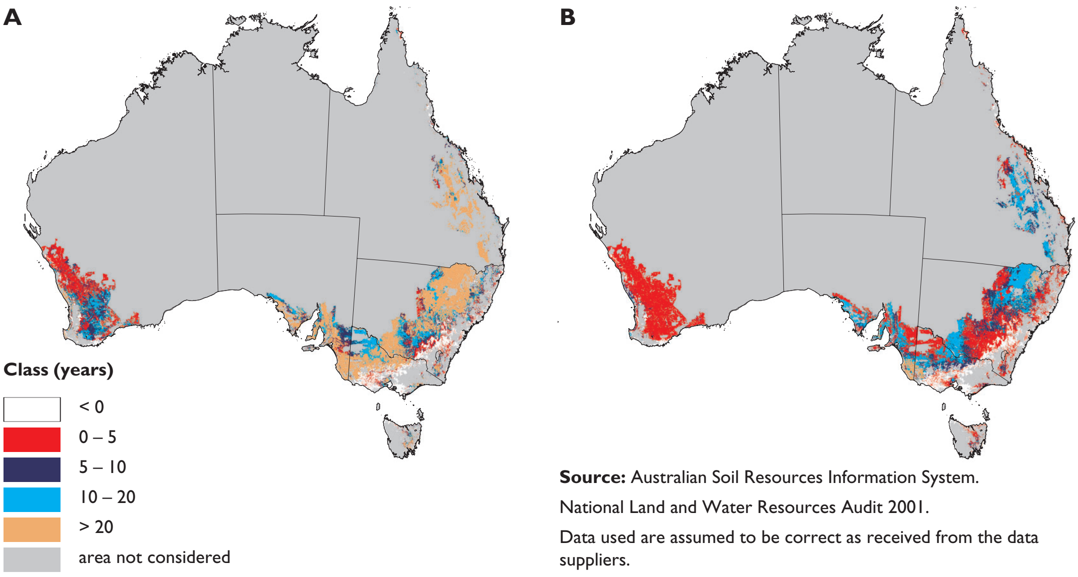
Table 4.9 National and State areas of agricultural land with pH greater than 4.8 and 5.5 and the predicted years to reach pH 4.8 and 5.5 at an acid addition rate of 50 (first number) and 250 (second number) kilograms lime equivalent per hectare per year.

	Currently acid	< 5 years	5[a] – 10 years	10[a] – 20 years	> 20[a] years	Total [b]
			(million hectares)			
pH 4.8						
New South Wales	5.0	3.9 – 15.5	3.6 – 6.8	5.8 – 9.3	19.2 – 0.9	32.6
Queensland	0.9	0.6 – 2.5	0.7 – 2.3	0.9 – 4.5	7.5 – 0.3	9.6
South Australia	0.2	0.5 – 4.8	2.1 – 2.3	1.9 – 4.2	7.1 – 1.5	11.6
Tasmania	0.6	0.3 – 0.7	0.1 – 0.6	0.2 – 0.1	0.4 – 0.0	1.0
Victoria	4.5	0.9 – 4.2	0.6 – 2.1	2.4 – 2.7	5.8 – 0.6	9.6
Western Australia	1.2	10.2 – 19.5	4.3 – 0.6	4.5 – 0.2	1.3 – 0.0	20.3
Australia [b]	12	16 – 47	11 – 13	16 – 21	41 – 3	85
pH5.5						
New South Wales	17.6	2.5 – 10.5	2.9 – 6.4	3.8 – 3.0	10.7 – 0.2	19.9
Queensland	2.4	0.7 – 3.2	0.7 – 3.9	1.0	5.7 – 0. 03	8.1
South Australia	1.0	1.3 – 5.2	2.3 – 1.8	1.3 – 3.2	6.0 – 0.7	10.9
Tasmania	1.6	0.0	0.0	0.0	0.0	0.0
Victoria	6.5	0.2 – 4.6	1.7	2.1 – 1.2	3.6 – 0.1	7.6
Western Australia	20.0	0.8 – 1.3	0.2 – 0.1	0.2 – 0.02	0.2 – 0.00	1.4
Australia [b]	49	6 – 25	8 – 14	8	26 – 1	48

a Inclusive

b Total values may be slightly different to summing values in the table because of rounding errors.

Figure 4.11 Modelled estimated years for Australia's agricultural soils (pH > 4.8) to reach pH_{Ca} 4.8 at minimum (A) and maximum (B) rates of acid addition, and in the absence of lime applications.

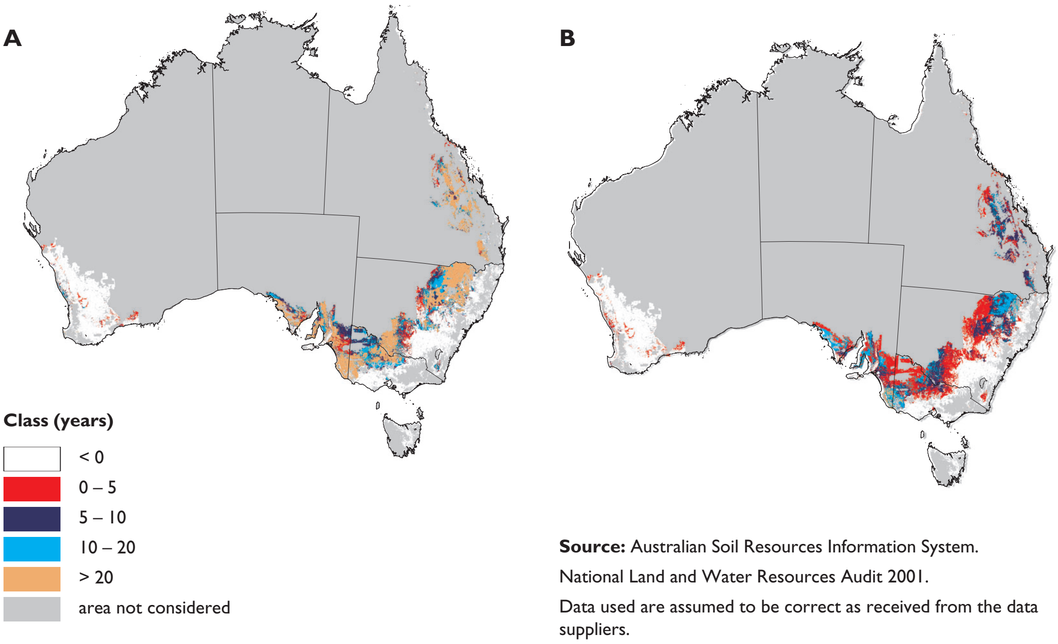


Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 4.12 Modelled estimated years for Australia's agricultural soils (pH > 5.5) to reach pH_{Ca} 5.5 at minimum (A) and maximum (B) rates of acid addition, and in the absence of lime applications.



Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Predictions for future soil acidification risk

Predictions of soil acidification risk (time to acidify) used two acid addition rates and required several modelled outputs:

- surface soil pH values above a pH of 4.8 or 5.5 (Figure 4.5);
- surface soil pH buffering capacity;
- acid addition rates equivalent to 50 and 250 kg lime/ha/year (Table 4.7 and Table 4.8).

The time taken to acid is calculated as follows:

Time (years) = [(pH current – pH critical) x pH buffering capacity]/acid addition rate

pH current is the modelled surface soil pH for each 250 m by 250 m cell (Figure 4.5, where pH current is greater than pH critical)

pH critical is either 4.8 or 5.5

pH buffering capacity is the modelled surface soil pH buffering capacity (Figure 4.10, tonnes of lime per hectare per pH unit) for each 250 m by 250 m cell

acid addition rate (tonnes of lime per hectare per year) is the amount of lime required to balance the acid input from agriculture.

Two acid addition rates were selected because of the large variation in acid addition rates from different farming systems and different environments, and difficulties in predicting future land use. They were equivalent to 50 and 250 kg of lime per hectare per year and cover most of the variation in the published acid addition rates. Some plantation fruit, such as bananas, can be as high as 2000 kg of lime per hectare per year, but the area affected is relatively small. Acid addition rates higher than 250 kg of lime per hectare per year can also occur for the broadacre crops, but are relatively isolated and do not occur every year.

This analysis assumes that:

- all acidification occurs in the surface soil, even though subsoil also acidifies—insufficient information exists for distributing acidification throughout the soil profile, since this varies with soil type and plant species;
- no liming materials were applied to soils—a conservative assumption for soils with pH values between 4.8 and 5.5. However, predicting which soils will or will not be limed in the future is impossible to determine.

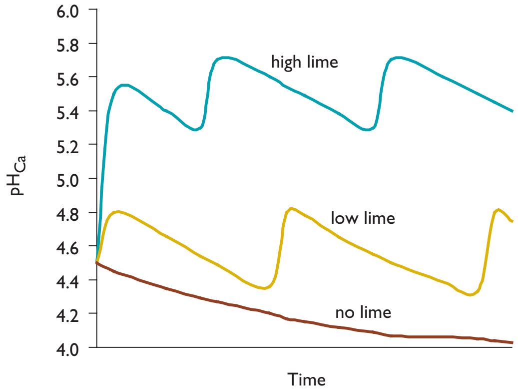
Application of liming materials to agricultural soils to alleviate soil acidity does not stop soil acidification. Rather acidification continues (*re-acidification*) at new soil pH level, and over time, surface-applied lime slowly exerts its effect at lower soil depths. Further applications of lime are an ongoing requirement (depending on rates of re-acidification).

Hypothetical examples of re-acidification (Figure 4.13) show that in the absence of lime application, soil pH continues to decline, while soil pH in the lime strategies are raised and then slowly fall, to be elevated again by more lime.

For lime application strategies to be effective we need to know:

- the amount of lime required to *adjust* the pH of existing acidic soils to the critical values of 4.8 and 5.5
- the amount of lime that will be required to *maintain* soil pH at around these values.

Figure 4.13 Hypothetical lime application regimes.



Consequences of liming strategies

The benefits of a high lime/higher cost strategy (maintaining pH around 5.5), compared to a zero lime/no investment strategy are:

- high plant yields;
- improved soil microbial activity and earthworm populations (in some soils);
- improved plant nutrition and water use;
- no loss of soil clay minerals;
- less impact from subsoil acidity; and
- greater ability to cope with subsequent re-acidification.

The low lime strategy (soil pH maintained around 4.8) has less positive impacts on these benefits. Some soil clay may be lost, yield potential of sensitive plant species may not be realised, and subsoil acidity may continue.

The zero lime strategy predicts slower rates of soil pH decline, because when acidic soils reach a pH of about 4.5, the pH buffering capacity increases because of the dissolution of soil clay minerals.

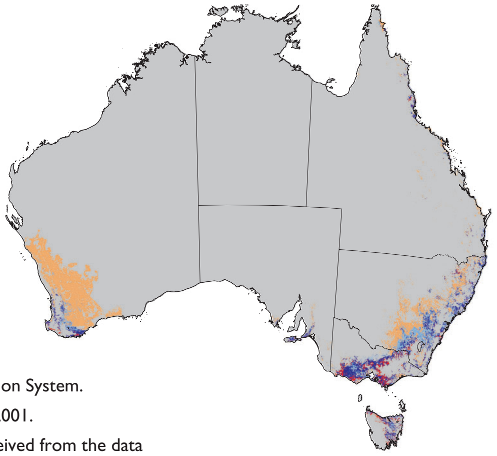
Adjusting the pH

The amounts of lime required to increase soil pH to the critical values of 4.8 and 5.5 were estimated and mapped (Figures 4.14, 4.15) for pH values in surface soils predicted to be less than 4.8 and 5.5 (low and high lime application strategies respectively). Amounts of lime were estimated from the product of pH buffering capacity and the difference between existing predicted and critical soil pH values.

- Most of Australia's acidic soil (78% or 38 million hectares) only requires relatively small amounts of lime (less than 2 tonnes lime per hectare) to increase the pH to 5.5 (Figure 4.15, Table 4.10). For many soils, this reflects the closeness of the current pH to 5.5 (Table 4.2) and their low pH buffering capacity (Table 4.5).
- Most of Australia's extremely or highly acidic soil (89% or 11 million hectares) require less than 2 tonnes of lime per hectare to achieve a pH of 4.8 (Figure 5.14, Table 4.5).

Figure 4.14 Lime application rates required to raise Australia's acidic soils to pH 4.8.

Figure 4.15 Lime application rates required to raise Australia's acidic soils to pH 5.5.



Source: Australian Soil Resources Information System.

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Table 4.10 Estimated State and national areas of existing acidic land (million hectares) and the predicted quantities of lime required to reach pH_{ca} of 4.8 and 5.5.

	< 1 t lime/ha	1[a] – 2 t lime/ha	2[a] – 5 t lime/ha	≥5 t lime/ha	Total[c]
			(million hectares)		
Critical pH 4.8					
New South Wales	4.2	0.5	0.2	0.0[b]	5.0
Queensland	0.5	0.2	0.1	0.0[b]	0.9
South Australia	0.2	0.0[b]	0.0[b]	0	0.2
Tasmania	0.3	0.2	0.2	0.0[b]	0.6
Victoria	2.5	1.3	0.6	0.1	4.5
Western Australia	0.8	0.2	0.1	0.0[b]	1.1
Australia[c]	8.5	2.5	1.1	0.2	12.3
Critical pH 5.5					
New South Wales	8.8	5.6	3.0	0.3	17.6
Queensland	1.3	0.5	0.5	0.1	2.4
South Australia	0.4	0.3	0.3	0.0	1.0
Tasmania	0.1	0.3	0.8	0.4	1.6
Victoria	0.6	1.1	3.4	1.3	6.5
Western Australia	17.5	1.5	0.9	0.1	20.0
Australia[c]	28.7	9.3	8.8	2.2	49.1

[a] Inclusive

[b] Numbers rounded to 0.0 vary from 0.01 – 0.04.

[c] Total values may be slightly different to adding up the values in the table because of rounding errors.

It is estimated that Australia needs to apply a one-off 12 and 66 million tonnes of lime to its acidic soils, to increase the pH to 4.8 and 5.5 respectively. Current agricultural lime use is nearly 2 million tonnes of lime per year (Table 4.11). If lime is applied to acidic soils at the current rate and no further acidification takes place, it would take six years to increase the pH to 4.8 and 37 years to 5.5. In the meantime, soils are continuing to acidify and this time frame is being extended.

This prediction strongly indicates there is a significant deficit in addressing soil acidification in Australian farming systems.

- Victoria and New South Wales require the highest amount of lime (Table 4.11).
- At current lime use, Western Australia and South Australia will overcome current acidity problems in a shorter time than other States (Table 4.11). Victoria will take the longest to overcome current acidity problems (Table 4.11).

Table 4.11 Total quantity of lime (million tonnes) required on a national and state level for acidic soils to reach a critical pH of 4.8 and 5.5 compared to actual lime use (million tonnes).

	Lime required pH 4.8	Lime required pH 5.5	Current lime use per year	Years to increase pH to 4.8 at current lime use[a]	Years to increase pH to 5.5 at current lime use[a]
New South Wales	3.0	22.2	0.5	7	49
Queensland	0.9	3.2	0.1	12	45
South Australia	0.1	1.5	0.1	1	15
Tasmania	1.1	6.3	0.2	7	42
Victoria	5.6	21.7	0.4	15	59
Western Australia	0.9	10.7	0.7	1	16
Australia	11.6	65.6	1.8	6	37

[a] Assumes current lime use and no further acidification.

Maintaining pH

The low and high lime strategies identified in Figure 4.13 also require periodic re-application of lime to counter subsequent soil re-acidification. These lime maintenance levels were estimated annually both for minimum and maximum rates of acid addition (Table 4.12).

Table 4.12 Total quantity of lime (million tonnes per year) required on a national and state level to maintain pH values at 4.8 and 5.5 using two acid addition rates (50 and 250 kg lime equivalent per hectare per year).

	pH 4.8	**pH 5.5**
New South Wales	0.25 – 1.25	0.88 – 4.41
Queensland	0.04 – 0.22	0.12 – 0.60
South Australia	0.01 – 0.06	0.05 – 0.25
Tasmania	0.03 – 0.16	0.08 – 0.41
Victoria	0.22 – 1.13	0.32 – 1.63
Western Australia	0.06 – 0.29	0.98 – 5.01
Australia	0.6 – 3.1	2.4 – 12.3

- National estimates indicate that for soil pH maintenance at 4.8 (low lime strategy), annual applications from 0.6 – 3.1 million tonnes of lime will be required. To maintain soil pH at 5.5 (high lime strategy), annual totals from 2.4 – 12.3 million tonnes will be required. Again, Western Australia and New South Wales are the States requiring the highest maintenance levels of application, followed by Victoria.
- These estimates indicate that Australia needs to apply between 12 and 66 million tonnes of lime to adjust soil pH to 4.8 or 5.5, with a further 1–3 or 2–12 million tonnes required nationally for pH maintenance. At present, approximately 2 million tonnes of lime are applied to agricultural lands each year.

Allowing for the assumptions and potential errors introduced by the resolution and quality of the input data sets into the spatial analyses, these results suggest a *very large lime deficit* exists in Australia's farm systems. These results merit further regional investigation into soil acidification—potentially one of the sleeping giants for on-farm productivity.

MANAGEMENT OPTIONS FOR ACIDITY

Helyar (1991) comprehensively reviewed concepts and practical issues for managing complex processes associated with soil acidification. This Australian review provided a useful framework for assessing future management options and current practices. With most of these strategies, reducing acidification is not the only consideration (e.g. ammonium-based nitrogen fertilisers may be easier to use). Targeting nitrogen fertiliser use, rather than relying on legumes to provide nitrogen can reduce acidification. Other considerations include the cost of nitrogen fertilisers, the income derived from crop legumes and the other benefits of a legume system (e.g. reduced weeds, pests and diseases of wheat).

Farm management options for dealing with soil acidity (Helyar 1991)

Principal issues

1. Controlling acid additions through better managing the nitrogen and carbon cycles
2. Use of plant tolerance to reduce the effect of acidic soil conditions
3. Use of liming materials to ameliorate acidic surface and subsoils
4. Applying fertiliser nutrients (e.g. molybdenum) to correct nutrient constraints caused by soil acidity

Management strategies

Nitrogen fertiliser

- Change nitrogenous fertiliser from ammonium-based sources to urea or anhydrous ammonia or nitrate-based products

Reducing nitrate leaching and improving nitrogen use efficiency

- Improve timing of nitrogen fertiliser application to match demand by plants
- Ensure nitrogen inputs do not exceed crop demands
- Ensure irrigation does not result in deep drainage
- Sow crops early (favouring early crop root growth) to improve efficiencies in use of fertiliser nitrogen and mineralised soil organic nitrogen reserves
- Grow perennial rather than annual species. In some regions, the existence of live plants during summer and autumn will increase nitrate uptake and thereby reduce leaching losses.
- Reduce legume dominance in mixed pastures
- Use reduced tillage to minimise build-up of soil nitrate (nitrate is more likely to leach when crop demand is low in early winter)
- Avoid long fallows
- Incorporate high carbon/nitrogen plant residues (stubbles) into the soil so that microbes use soil nitrogen to break down residues, thus preventing nitrate from being leached

Carbon cycle

- Retain plant residues on-site rather than burning or removing
- Return plant residues to areas of active root growth (e.g. in row or plantation crops, return residues to the crop row)
- Manage stock to disperse campsites (e.g. by reducing the size of the paddocks or increasing the intensity of grazing)
- Graze pastures rather than cut for hay or silage
- If hay is required, feed hay in the paddock where it was cut

Acid tolerant plants

- Use acid-tolerant perennials in favour of annuals
- Adopt acid-tolerant strategies where lime amelioration is too costly

Lime applications (preferred where economically feasible)

- Lime will also stimulate nutrient availability in acidic soils
- Use of earthworms and dung beetles speeds incorporation and downward penetration of surface applied lime to help ameliorate subsoil acidity
- Mechanical mixing and injections of lime have also been used in some areas

Lime

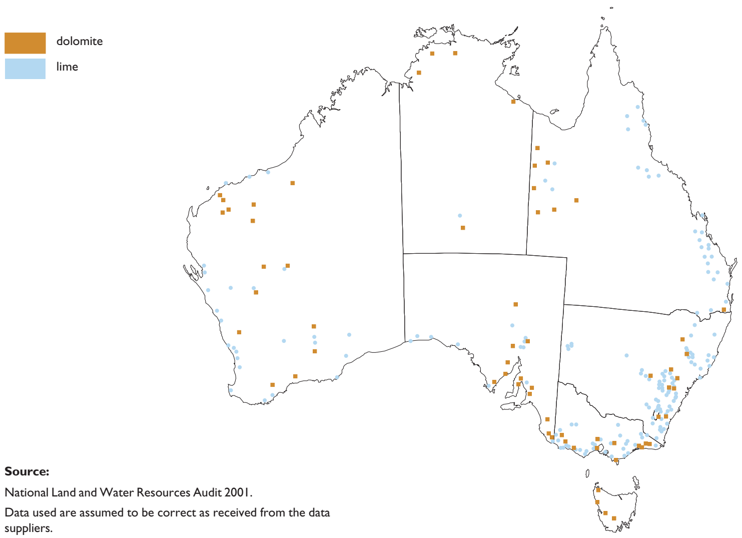
Even where soil acidity and the benefits of lime applications are recognised by farmers, liming may not be tenable because:

- lime is required in large amounts (1–5 t/ha) and it may have to be transported a long way from where it is mined (Figure 4.16) and hence is expensive;
- profitability in some farming sectors is declining (e.g. in Queensland low sugar prices have dramatically reduced lime use in recent years); and
- surface applications of lime to correct subsoil acidity may take many years before improvements are realised

High value industries (e.g. horticulture), where fertiliser is a small proportion of the total operating cost, are more likely to use lime compared to broadacre dryland farming industries. Broadacre industries are often located a long way from where the lime is mined and have lower profit margins, increasing the relative costs of lime use. At the same time, their farming practices induce acidification over larger areas of land.

- Including cartage and spreading costs, an application of 2.5 t/ha, costs will vary from $145 to $200 per hectare in Queensland to $52 to $110 per hectare in Western Australia and $45 to $100 per hectare in South Australia.

Figure 4.16 Location of lime and dolomite deposits in Australia.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Growing acid-tolerant species

Some plants are able to tolerate more acid soils. Species with acid tolerance (see also Table 4.13) include: triticale, oats, yellow lupins, clover, perennial veldt grass, subterranean clover, perennial rye-grass, cocksfoot and tall fescue (in temperate regions); and sugar cane, macadamias and bananas (in subtropical regions).

Clay spreading

Spreading sodic clays to alleviate water repellent soils in South Australia also increases soil pH in the zone of incorporation.

Use of alkaline irrigation water

Soils irrigated from bores in South Australia are known to significantly increase soil pH.

Table 4.13 Estimated agricultural lime/dolomite production and use in thousands of tonnes.

	Production			Use
	1989/90[b]	1995/96[c]	1998/99[a]	1995/96[c]
New South Wales	144	335	453	257
Queensland	150	246	70	144
South Australia	40	88	100	31
Tasmania	100	99	150	146
Victoria	147	281	370	197
Western Australia	117	178	653	178
Australia	**708**	**1242**	**1811**	**958**

[a] Data are from surveys of lime producers (Victoria, South Australia, New South Wales), State Department of Mines (Tasmania, Queensland) or survey of farmers on lime and dolomite use (Western Australia, Australian Bureau of Statistics data). Alkaline by-products were not considered. There is also some transport of lime across state borders.

[b] Adapted from Porter & McLaughlin (1992).

[c] Adapted from CRC Soil & Land Management (1999).

CASE STUDY

Acidification case study: bananas in tropical north Queensland

Industry scenario

- A survey of 'current practice' at three commercial banana plantations indicated growers applied an average of about 600 kg N/ha/year predominantly as urea, but with some ammonium nitrate also being used.
- Banana bunches removed from plantations averaged about 8100 kg dry weight/ha/year with an alkalinity equivalent to 200 kg agricultural lime/ha.
- Nitrate leaching losses in excess of 50 kg N/ha/year have been measured under bananas in the wet tropics. This area receives over 3000 mm annual rainfall.
- During de-suckering, crop residues (suckers and dead leaves) are disposed into inter-row areas.

Estimates of acidification rates

- Contributions to soil acidification in the banana production system include nitrate leaching from applied fertiliser, organic matter accumulation (acidifying), removal of alkalinity in harvested product, removal of alkalinity in crop residues such as suckers and dead leaves during de-suckering, and application of ammonium-N (acidifying) which is balanced by the application of the equivalent amount of nitrate-N (alkalising) where ammonium nitrate is used as the nitrogen fertiliser (Figure 4.17).
- The net acidification under these current practices is managed by regular surface applications of agricultural lime or dolomite at rates of 1–2 t/ha/year.

Practices for reducing acidification

Identification of the sources of acidification and their magnitude under current practices allowed a best management practice scenario to be developed. This scenario involved:

- reducing nitrogen input to 250 kg N/ha/year;
- applying nitrogen fertiliser in the form of ammonium nitrate rather than as urea;
- returning crop residues to the plant row rather than discarding into the inter-row; and
- reduced nitrate leaching as a consequence of reduced nitrogen fertiliser inputs.

Has best practice management worked?

Confirmatory evidence that adoption of best management practices would have a positive impact on reducing acidification was obtained by comparing 'paired site' data from a commercial plantation using *current practices* and another plantation that has implemented some of the *best management* practices detailed above. In the 'paired site' approach, soil pH was measured to a depth of 1 m under bananas and under rainforest (i.e. the undeveloped situation) in close proximity on the same soil type (see Figure 4.18).

- *Best practice* management has resulted in a net increase in soil pH to a depth of 40 cm (Figure 4.18a).
- Subsoil acidification has occurred under *current practice* (Figure 4.18b) despite the regular surface application of agricultural lime. Lime applications have caused pH in the surface 20 cm to increase, but had no effect below 20 cm. The correction of subsoil acidification is expensive and prevention is the best option.

Industry implications

The banana industry is moving towards adoption of these best management practices as research removes some of the uncertainties associated with current fertiliser and plant residue management (e.g. it has been shown that nitrogen fertiliser inputs can be reduced to around 250 kg N/ha/year where fertigation is used; a major improvement in fertiliser nitrogen efficiency; fertigation also allows flexibility in the form of fertiliser applied).

The use of nitrate fertilisers in the industry is expected to increase as growers become aware that reduced acidification rates occur where nitrate rather than ammonium fertilisers are used. In addition, reduced nitrate leaching under best management practices will reduce nitrate contamination of surface and groundwaters.

Further information

Moody P.W. & Aitken R.L. 1997, 'Soil acidification under some tropical systems. 1. Rates of acidification and contributing factors', *Australian Journal of Soil Research* vol. 35, pp. 163–173.

Figure 4.17 Sources of acidification expressed as the amount of lime required to neutralise the acidity generated under current and best management practices for bananas grown in north Queensland.

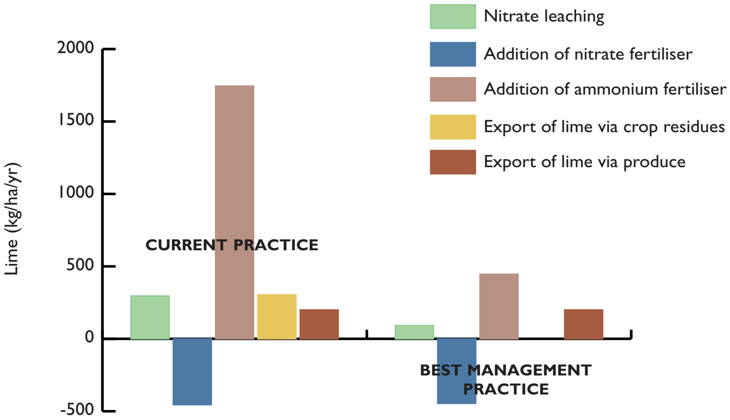
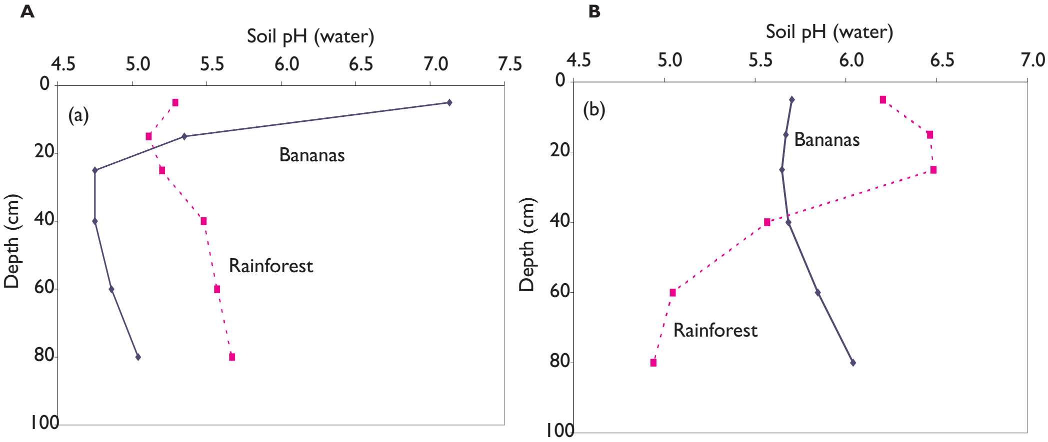


Figure 4.18 Soil profile pH under rainforest and bananas managed by (A) best management practice and (B) current management practice.



IMPACTS OF ACIDIC SOIL CONDITIONS ON PLANT YIELD

Soil acidity:

- reduces the availability of essential plant nutrients to plants;
- detrimentally affects microbial soil processes, legume nodulation and nitrogen fixation; and
- induces the dissolution and accumulation of toxic levels of aluminium and sometimes manganese in soils.

Moderately acidic soils reduce growth of some legume species; while highly and extremely acidic soils are suboptimal for the growth of most agricultural plant species. Under these conditions, plant growth can be impaired by:

- toxic concentrations of aluminium and manganese that accumulate in the acidic environment and seriously impede root growth (occurs below pH 4.8 and leads to reduced shoot growth, and inefficient use of soil water and nutrients; manganese toxicity is also observed more frequently on less weathered soils);
- reduction in nodulation in legumes;
- unavailability of essential plant nutrients (e.g. phosphorus and molybdenum); and
- depression of nutrient cycling through adverse effects on soil biological processes.

Different plants have different tolerances to soil acidity (Table 4.15). Between a pH of 4.8 and 5.5, growth of very highly to highly acid sensitive species, mainly legumes, will be reduced. Below pH 4.8, plant growth starts to be progressively depressed by aluminium and manganese toxicity and other acidity-related disorders. At pH values below 4.3, the yields of most plant species are markedly reduced. Soil pH is the most common test used in determining whether acid soils are restricting plant growth, because soil tests for aluminium and manganese are not yet available to assist farmers.

Plant yield declines with decreasing surface soil pH (Figure 4.19). The extent of the decline depends on the concentration of aluminium and manganese in each soil. Subsoil acidity also reduces the growth of plant species.

The yield relationships were used to estimate economic penalties associated with farming acidic soils in Australia's agricultural regions, using plant species differing in tolerance to acidic soil conditions. These assessments were also contrasted where lime had been applied to alleviate soil acidity. These findings are reported in the Audit's socioeconomic report (*Australians and Natural Resource Management 2001*).

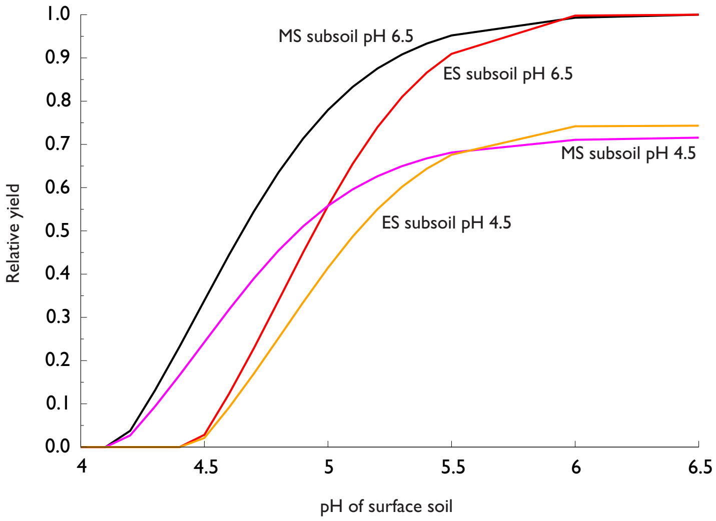
Table 4.14 Allocation of plants to each yield tolerance class indicates the tolerance to aluminium, manganese and pH (cultivars do vary in their tolerance so the table can only be taken as a guide).

Tolerance class	Examples
Extremely tolerant	Italian and perennial rye-grasses, lovegrass, oats, native pasture[a], pineapple, sugar cane, yellow serradella
Highly tolerant	Bananas, cereal rye, cocksfoot, lupins, macadamia, peanuts[b], potatoes, rice, triticale, turf
Moderately tolerant	Avocados, cotton, maize, mangoes, Rhodes grass, soybeans, subterranean clover, wheat
Slightly tolerant	Crimson clover, grain sorghum, *Medicago murex*, millet, mustard, phalaris
Slightly sensitive	Buffel grass, Faba beans, field peas, vetches, white clover
Moderately sensitive	Almonds, apricots, barley, canola, cherries, fennel, grapes, lavender, mandarins, nectarines, oranges, peaches, pears, plums, red clover, sunflower, tobacco
Highly sensitive	Apples[b], balansa clover, chick peas, coriander, lentils, lucerne, mung beans, oil poppies, pyrethrum
Extremely sensitive	Persian clover, strand medic, strawberry clover, tall wheatgrass

[a] Tolerance depends on soils at origin.

[b] Very sensitive to calcium deficiency, which can occur on acid soils.

Figure 4.19 The effect of surface soil pH_{Ca} on yield of highly and slightly tolerant, and moderately and extremely sensitive plant species on relative.



IMPLICATIONS FOR AUSTRALIAN AGRICULTURE

Acidification looms as a major soil degradation issue in all Australian States, and farmer awareness of its insidious nature has been heightened in recent years by research and extension programs in some, but not all States. At present, only three States (Western Australia, New South Wales and South Australia) have active extension programs on soil acidity.

Problems arising from induced acidification are reversible (mostly), but costly. This means that farmers only treat small areas of their farms with lime at any one time, where liming is an economically viable option.

- Efficiency in lime use could be achieved by basing application rates on soil types, as variations exist in the amounts of toxic aluminium and manganese in the soil solution at a given pH.
- Innovative ways for treating subsoil acidity and subsoil acidification processes remains a priority for future research.

Farmers responses to treating soil acidity are partly attributed to preserving or enhancing the capital value of their farm. Regional resource managers are also concerned with wider implications of soil acidification on the resource base. Reduced plant growth due to soil salinity can lead to increased erosion, less water use (increasing recharge to groundwater) and downstream effects of sedimentation and possibly salinity.

Understanding off-site impacts from soil acidification on-farm are rudimentary and need to be assessed with scientific rigor. To date, some postulations have been assembled, but not tested. Significant off-site implications would move soil acidification into the ‘public good’ arena. By far the best option would be to treat soil acidification on farm before it becomes a downstream issue.

REFERENCES

Anderson G.C., Fillery I.R.P., Dunin F.X, Dolling P.J & Asseng S. 1998, 'Nitrogen and water flows under pasture–wheat and lupin–wheat rotations in deep sands in Western Australia. 2. Drainage and nitrate leaching', *Australian Journal of Agricultural Research* vol. 49, pp. 345–361.

Ahern C.R., Baker D.E. & Aitken R.L. 1995, 'Models for relating pH measurements in water and calcium chloride for a wide range of pH, soil types and depths', *Plant & Soil* vol. 171, pp. 47–52.

Aitken R.L., Moody P.W. & McKinley P.G. 1990, 'Lime requirement of acidic Queensland soils. I. Relationships between soil properties and pH buffer capacity', *Australian Journal of Soil Research* vol. 28, pp. 695–701.

CRC Soil & Land Management 1999, *The costs of soil acidity, sodicity and salinity for Australia: Preliminary estimates*, Cooperative Research Centre for Soil and Land Management, Glen Osmond, South Australia.

Dolling P., Moody P., Noble I., Helyar K., Hughes B., Reuter D. & Sparrow L. 2001, *Soil acidity and acidification in Australia*, National Land and Water Resources Audit Project Report.

Helyar K.R. & Porter W.M. 1989, 'Soil acidification, its measurement and the processes involved', in A.D. Robson (ed.), *Soil Acidity and Plant Growth*, Academic Press, Sydney, NSW.

Helyar, K.R 1991, 'The management of acid soils', in R.J. Wright, V.C. Baligar & R.P. Murrmann (eds), *Plant–soil interactions at low pH*, Kluwer Academic Publishers, Netherlands.

Hollier C. 1999, *Acid Soil Action. A practical decision support guide to assess the problem and manage the risk*, Department of Natural Resources and Environment.

Moody P.W. & Aitken R.L. 1997, 'Soil acidification under some tropical systems. 1. Rates of acidification and contributing factors', *Australian Journal of Soil Research* vol. 35, pp. 163–173.

NLWRA (in press) *Australians and natural resource management 2001*, report of the National Land and Water Resources Audit.

Noble A.D., Cannon M. & Muller D. 1997, 'Evidence of accelerated soil acidification under Stylosanthes-dominated pastures', *Australian Journal of Soil Research* vol. 35, pp. 1309–1322.

Heng L.K, White R.E., Helyar K.R., Fisher R. & Chen D. 2001, 'Seasonal differences in the soil water balance under perennial and annual pastures on an acid Sodosol in southeastern Australia', *European Journal of Soil Science* vol. 52, pp. 227–236.

Porter W.M. & McLaughlin M.J. 1992, *Evaluation of the use of agricultural lime in Australia*, Grains Research and Development Corporation.

Ridley A.M., White R.E., Helyar K.R., Morrison G.R., Heng L.K. & Fisher R. 2001, 'Nitrate leaching loss under annual and perennial pastures, with and without lime on a duplex (texture contrast) soil in humid southeastern Australia', *European Journal of Soil Science* vol. 52, pp. 237–252.

WATER-BORNE SOIL EROSION

SUMMARY

- Dominant erosion processes vary from sheetwash erosion in Queensland, to gully erosion over much of southern Australia and streambank erosion particularly in eastern Victoria.

Predicted sheetwash and rill (hillslope) erosion*

- Less than 5% of the potential 1.2 billion tonnes of soil moved each year on hillslopes is predicted to contribute to stream sediment loads.
- The average erosion rate is 4.4 t/ha/yr in the area assessed.
- On average, current hillslope erosion is three times higher than the natural rate.
- 39% of the continent experiences low hillslope erosion (< 0.5 t/ha/yr); 11% with high erosion risk (> 10 t/ha/yr); and 50% with medium erosion potential (0.5–10 t/ha/yr).
- Overall, 23% of the area is eroding at a rate greater than the continental average rate, showing the value of targeting erosion control to particular problem areas.
- The biggest total contribution to soil erosion in Australia is from the vast semi-arid woodlands and grazing lands in northern regions. Low inputs, low returns and huge areal extent make this hard to manage. Maintenance of adequate ground vegetation cover is the key practical solution.
- The highest rates of soil erosion are from intensively cropped lands, particularly tropical croplands. Much has been done to reduce these rates through minimum tillage, soil conservation works, and stubble retention. Soil erosion risks still remain—maintaining adequate vegetative cover at times of high erosion risk is critically important. Riparian management is the most practical last line of defence.

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* The assessment of the impact of land use practice on erosion rates could not be undertaken due to a lack of spatial information.

SUMMARY

Gully and riverbank erosion

- In southern Australia, gully and river bank erosion are the dominant sources of sediment supplied to streams.
- Two-thirds of streams assessed (approximately 120 000 km of stream length) are cleared of native riparian vegetation, well beyond current restoration efforts. Targeted restoration is required along streams and rivers where sediment and other riparian issues limit river health.
- Some 325 000 km of gullies across the assessment area have eroded about 4.4 billion tonnes of sediment since European settlement.
- 30% of the Murray–Darling Basin has moderate or high density (i.e. > 1 km/km^2) of gully erosion, most of which are not actively forming but remain significant suppliers of sediments to rivers.
- Gully erosion in southern Australia has been largely stabilised, but they are still actively forming in northern Queensland and in some agricultural regions of Western Australia.
- Gully sediments remain a cause of poor water quality requiring targeted restoration.

River sediment loads and deposition

- Gully, riverbank and sheetwash erosion deliver over 120 million tonnes of sediment to streams each year.
- 30 000 km of streams (including 30% of southern Western Australia and 20% of the Murray–Darling Basin) have sand and gravel derived from gully and streambank erosion, to the extent that in-stream ecological health is significantly impaired.
- 14 million tonnes of sediment is transported to the Queensland coast and 3 million tonnes to the New South Wales coast each year.
- River sediment loads are generally 10 to 50 times greater than pre-European loads in intensively used river basins.
- Ninety per cent of the suspended sediment loads reaching estuaries are derived from 20% of catchment areas, forming a basis for targeted sediment control.
- Deposition of sand and suspended sediments in streams and rivers are greatest in the Murray–Darling Basin, coastal regions of New South Wales, south-east Queensland and the Glenelg region of Victoria—areas of significant vegetation clearance and high intensity rainfall events.

Soil erosion is a natural process—occurring more in landscapes with high rainfall intensity or steep slopes. The shallow stony soils that cover much of the coastal ranges and the steeper semi-arid lands have been naturally eroded. Where the protective vegetation cover is removed or degraded by clearing, tillage or overgrazing, risks of sheetwash erosion are increased and rill and gully erosion occur. Associated degradation of riparian vegetation has also accelerated erosion of creek and river banks. In arid and semi-arid landscapes, reduced vegetation cover also accelerates wind-borne erosion (to be reported in the 2001 *Australian State of Environment Report*).

Soil erosion can reduce on-site productivity through loss of fertile topsoil, and associated water-holding capacity and nutrients. Intense erosion also leads to soil structural decline and poor plant growth.

Soil erosion also has the potential for downstream impacts on creeks, rivers, reservoirs, lakes, and estuarine and marine environments. Water-borne erosion increases the supply of sediment to rivers. High concentrations of suspended sediments in rivers can:

- reduce stream clarity;
- inhibit respiration and feeding of stream biota;
- diminish light needed for plant photosynthesis;
- require treatment of water for human use;
- smother the stream bed; and
- increase land flooding.

Increased supply of sand and gravel from gully and riverbank erosion has led to deposition of sand and gravel beds (*sand slugs*). Sand slugs smother aquatic habitat. They can prevent fish passage, fill pools and other refugia and are unstable substrates for river bed life.

ASSESSING WATER-BORNE EROSION AND SEDIMENT TRANSPORT

Soil erosion on agricultural land was assessed and placed in the context of river basin sediment budgets. Potential downstream impacts were identified and areas for continuing management attention are highlighted. These build upon major progress made since the 1930s through soil conservation activities to prevent erosion. The assessment includes improved prediction of sheetwash and rill erosion, and the first national assessments of gully erosion, streambank erosion, river sediment loads and deposition of sediment. Most significantly, the work is the first to explicitly relate patterns of sub-catchment erosion to downstream loads and export. The framework should prove valuable for future regional target setting and resource planning.

Assessing water-borne erosion

The assessment of water-borne erosion and river sediment transport covered:

- sheetwash and rill erosion (also termed hillslope erosion potential);
- gully erosion;
- riverbank erosion; and
- transport and delivery of eroded sediments through rivers and to estuaries.

Extent of assessment

The whole continent was assessed for sheetwash and rill erosion. Assessment areas for the other components took place at locations of intensive land use and their surrounding catchments—geographically the catchments of the east coast (extending from Cape York to the Eyre Peninsula), Tasmania and the south-west of Western Australia (Figure 5.1). Complete river basins were used to put intensive land use in the context of their hydrological catchments and to predict river sediment loads. Most river basins also include non-intensive land uses (e.g. forestry and rangelands).

Data

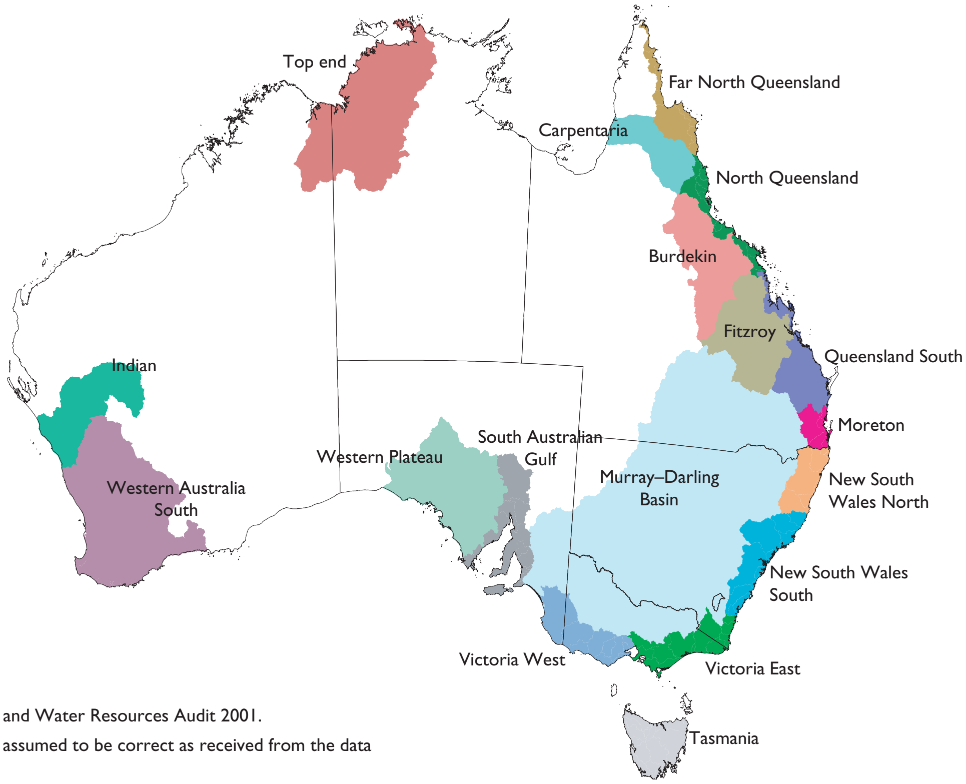
The assessment area was divided into 15 regions based upon drainage divisions and finer boundaries for summarising regional patterns (Figure 5.1). Data for modelling sediment loads in the Timor Sea, Gulf of Carpentaria and Western Plateau Drainage Divisions were inadequate.

Data on erosion rates and river sediment loads are limited with no erosion information available for many basins. Any national assessment must interpolate and extrapolate known data into areas with none. Fortunately, we have a good understanding of the processes of sediment transport and adequate data were available on the factors that control these processes, including comprehensive stream gauging records, digital elevation models, rainfall records and remote sensing of land cover.

The assessment used all available information—collecting further data where practical—and these were inputs to a relatively simple conceptual model* of the main drivers of sediment transport for large catchments. Process knowledge was used to constrain interpolation and extrapolation rather than relying on statistical associations between variables or on geographical interpolation. Statistical models were used for aspects where there was no adequate, large-scale, process understanding (e.g. for extent of gully erosion and width of river channels).

Soil loss and sediment movement predictions are outputs from sophisticated data-mining techniques and were implemented after evaluation. The river sediment model was developed to integrate the erosion process in detail across environmentally diverse catchments. It represents a major advance in available techniques for assessing regional river sediment loads and is also of value for more detailed regional assessment of sediment-related issues (e.g. downstream water quality, river health and catchment restoration).

Figure 5.1 Grouping of river basins with intensive agriculture for regional reporting.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

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* A conceptual model is one where simplified constructs of the physical processes are used (in this case, constructs for sediment transport at the large catchment scales).

Sheetwash and rill erosion

Controls on sheetwash and rill erosion are well understood and several models that incorporate these factors exist. The Revised Universal Soil Loss Equation (RUSLE) (Wischmeier & Smith 1978, Renard et al. 1997) was used to predict mean annual sheetwash and rill erosion potential across Australia under the current land use. Methods used to assess sheetwash and rill erosion are given in Lu et al. (2001a, 2001b) and Gallant (2001), including details of verification of the method against 100 observations of soil erosion rates.

The RUSLE calculates mean annual soil loss (tonnes/hectare/year) as:

$$\text{Annual soil loss} = R \times K \times L \times S \times C \times P$$

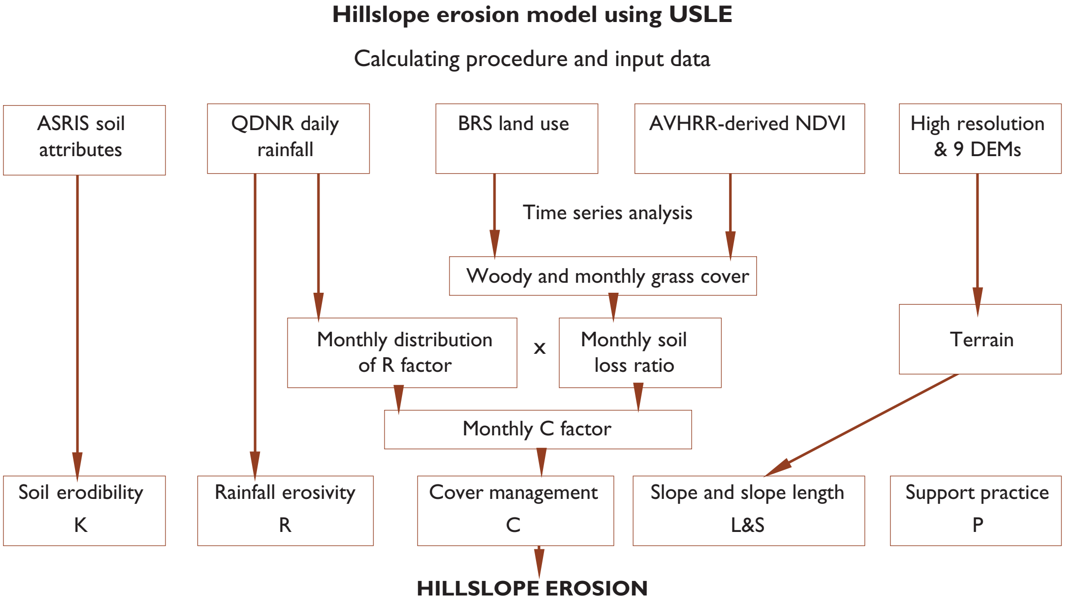
Where:

R is rainfall erosivity factor
K is soil erodibility factor
L is hillslope length factor
S is hillslope gradient factor
C is ground cover factor
P is land use practice factor

RUSLE variables differ considerably across the Australian continent. RUSLE provides a method for estimating spatial patterns of erosion using consistent information for each factor. Limited spatial data for contour cultivation and bank systems, meant that an assessment of land use practice was not possible. *Hence, reductions in soil loss due to use of soil and other conservation practices in intensive land use areas were not predicted.*

Innovative use was made of time series, remote sensing imagery and daily rainfall when combined with updated spatial data for soil, land use and topography. Problematic to the standard annual application of the RUSLE is the pronounced wet-dry precipitation regime in Australia's tropics and Mediterranean climate areas. To overcome this limitation, the model was applied to RUSLE on a monthly averaged basis (calculating appropriate erosivity and cover factors for each month) to represent the erosive potential of rainfall for each temporally distinct period. It used 20 years (1980–1999) of daily

Figure 5.2 Schematic implementation of the Revised Universal Soil Loss Equation.



rainfall data mapped across Australia (Jeffrey et al. 2001) and 13 years (1981–1994) of satellite vegetation data for this purpose. Mapped soil properties from the Australian Soil Resources Information System (Appendix 2), and land use mapping (see Figure 1.2) were used together with new techniques to derive fine scale hillslope topography from the coarse resolution national digital elevation model.

Limitations in the resolution of the data sets are evident where predictions of hillslope erosion are clearly overestimated in areas where land use is classified as grazing but grazing pressure/ stocking rates are low such as the basins north of Stewart Basin in Far North Queensland (including Jacky Jacky and Olive-Pascoe). However, the modelling predictions do serve to highlight the potential sensitivity of these environments.

Predictions of sheetwash erosion under present land use needed to be put in context of erosion under native vegetation cover. Natural or 'pre-European' erosion was predicted using the same procedure, with a cover factor for native vegetation and keeping the other factors of soil erodibility, rainfall erosivity and topography as for the present day. The cover factor for native vegetation before agricultural development was determined by interpolation and extrapolation. This was based on the climatic, topographic and geological characteristics of the current distribution of native vegetation.

Gully erosion

Gully erosion was mapped by predicting the density of gullies across the assessment area. Gully density is measured as the kilometre of gully length per square kilometre of land. It was assessed by interpreting aerial photographs.

Three separate data sources were used across the assessment area:

- Victoria: a map of gully density was provided by the Department of Natural Resources and Environment based on mapping by Lindsay Milton and Ian Sargeant (Ford et al. 1993).
- New South Wales and the Queensland part of the Murray–Darling Basin: data from the New South Wales 1988 land degradation survey were used (Graham 1989). A decision tree model was built to map gully erosion from the observations made and from geographical data of environmental factors.
- No analyses were available for the rest of the assessment area, so gullies were mapped on more than 350 stereo pairs of aerial photographs sampled across the area. These data were used to build decision tree models of gully density. Many environmental attributes were used to determine those that had the greatest ability to predict gully density. Attributes used included land use, geology, soil texture, rainfall and indices of seasonal climate extremes. Gully density was converted to mean annual erosion rate using gully age and volume. Details of the methods used are given in Hughes et al. (2001).

Streambank erosion

All streams with a catchment area greater than 50 km^2 and a length greater than 5 km were mapped across the assessment area. The proportion of stream with cleared native riparian vegetation was determined by intersection of the streams with coverage of native vegetation in 1995 (Australian Land Cover Change project, resolution of 100 m; BRS 2000). These data are only a crude measure of riparian condition as the 100 m resolution fails to identify narrow bands of remnant riparian vegetation in cleared areas and narrow valleys of cleared land penetrating otherwise uncleared land.

Erosion was assumed to only occur on sections of river with cleared riparian vegetation. The mean annual rate of bank erosion was calculated as a function of bankfull discharge to reflect globally observed patterns of erosion rate.

Sediment transport through river networks

The SedNet model (*Sed*iment river *Net*work model) developed for this assessment constructed a mean annual sediment budget sequentially downstream through each link* of a river network. A sediment budget accounts for:

- all the additions of sediment to a river;
- all the losses to deposition; and
- the net export of sediment.

It is essential to predict deposition because only a small proportion of the sediment supplied to river systems is actually exported to the mouth. Separate sediment budgets were constructed for bedload and suspended load because of the quite different transport processes.

Hillslope, gully and bank erosion, and upstream sediment export all deliver suspended sediment (fine-grained sediment suspended in the river water column) to a river link (Figure 5.3) during storms and floods. This contributes to flow turbidity. It also carries substantial amounts of nutrients (see *Nutrient loads to Australian rivers and estuaries* section).

Floodplains and reservoirs are the main areas of net deposition of suspended sediment. Deposition was modelled using a simple 'sediment residence time' approach.

Bedload is the coarse sand, gravel and stones that roll and bounce down the bed of a river. Net deposition occurs on the bed when the loading over time exceeds the sediment transport capacity of the stream (Figure 5.4). Sediment transport capacity is the maximum amount of sediment that a river can carry given its discharge, slope, width and hydraulic roughness. All sediment in excess of capacity is deposited, changing the morphology of the river and

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* A link is the stretch of river between tributaries.

impacting on the physical habitat. If the total loading over time is less than the transport capacity, then all sediment is delivered downstream and there is no change to habitat. To predict the location of sand slugs, bedload deposition was expressed as the depth of accumulation since European settlement.

Methods used to construct budgets for river sediment (Prosser et al. 2001) included detailed mapping of floodplains (Pickup & Marks 2001), synthesis of extensive river gauging records, and measurements and modelling of river widths. Predictions have been validated against a range of indicators, including observed river sediment loads.

The SedNet model calculates:

- mean annual suspended sediment output from each river link;
- depth of sediment accumulated on the river bed in historical times;
- mean annual rate of sediment accumulation in reservoirs;
- mean annual export of sediment to the coast; and
- contribution of each sub-catchment to that export.

Figure 5.3 Conceptualisation of the suspended sediment budget for a river link.

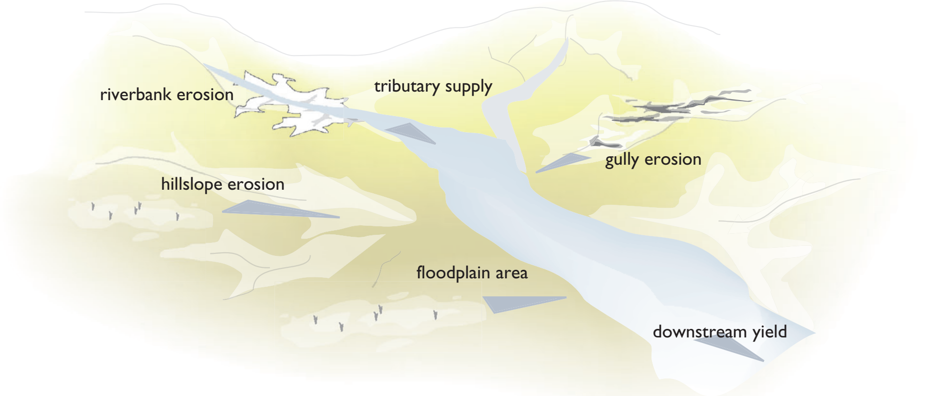
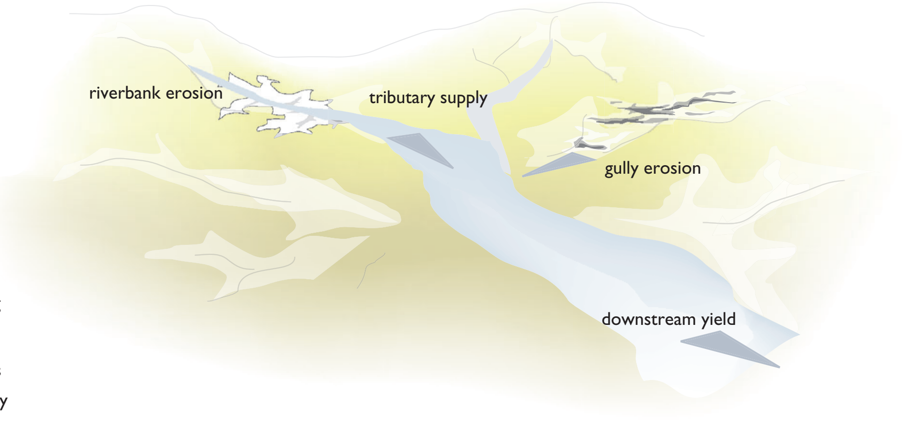


Figure 5.4 Conceptualisation of the bedload budget for a river link.



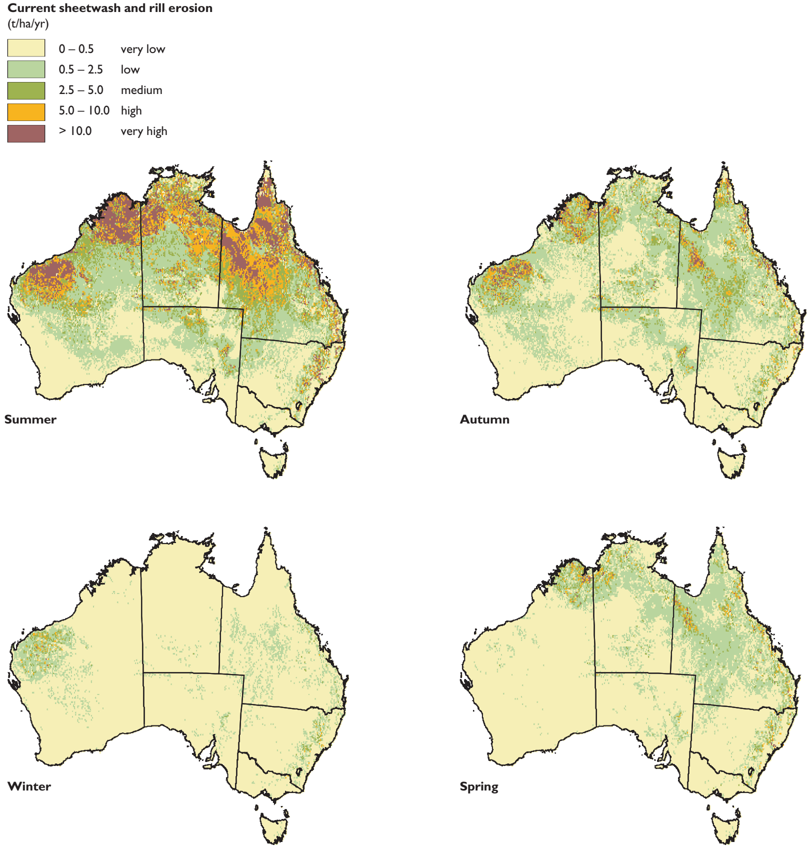
If loading < capacity:

- no deposition
- yield = loading

If loading > capacity

- deposit excess
- yield = capacity

Figure 5.5 Mean annual sheetwash and rill erosion rate.



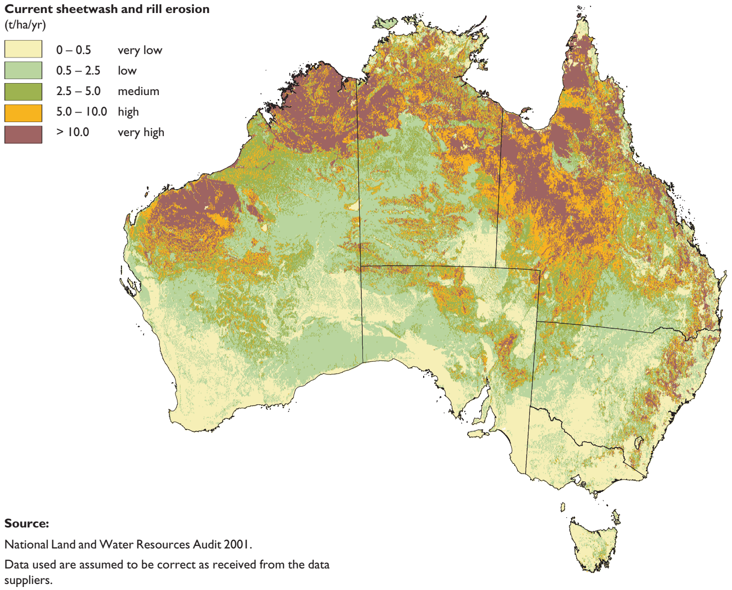
CONTINENTAL SHEETWASH AND RILL EROSION

Northern Australia has higher predicted erosion potential than the south (Figure 5.5)—northern summer rains are highly erosive and can coincide with relatively little ground cover. A zone of high potential erosion also occurs on the western slopes of the Great Dividing Range along the belt of cereal cropping land. Winter is the most erosive season in southern Australia, but where rains fall on well vegetated land erosion potential is negligible.

Results of this modelling represent soil erosion potential because:

- no comprehensive assessment could be made of the reduction in soil erosion under some cropping land uses that have been achieved through conservation practices, such as minimum tillage, contour banks and stubble retention; and
- the naturally high soil erosion potential on steeper slopes in northern Australia results in soils with significant stone and rock cover, reducing the actual rate of erosion. No data were available to model this phenomenon.

Figure 5.5 Mean annual sheetwash and rill erosion rate.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Each year, 1.2 billion tonnes of soil has the potential to be moved on hillslopes in river basins containing intensive land use. Using the classes represented in Table 5.1, 11% of Australia experiences high sheetwash and rill erosion potential. About 23% of the area is eroded at a rate greater than the continental average of 4.4 t/ha/yr. These statistics show the value to be gained from targeting erosion control to particular problem areas.

The implications of sheetwash and rill erosion for farm productivity have not been assessed.

Table 5.1 Sheetwash and rill erosion rates divided into three classes.

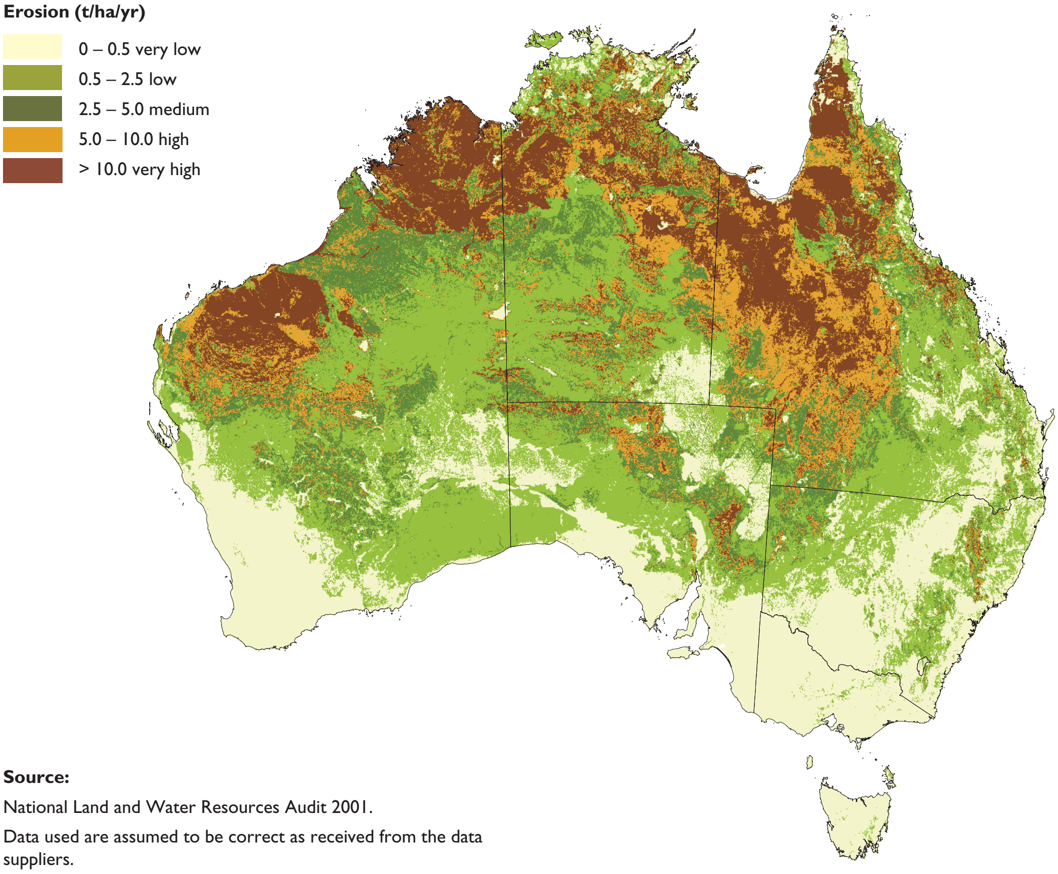
Erosion rate	Volume (t/ha/year)	Proportion of land (%)
Low	< 0.5	39
Medium	0.51 – 9.9	50
High	> 10	11

Pre-European sheetwash and rill erosion

Comparisons of current soil erosion potential to that of pre-European settlement conditions under native vegetation cover were needed to understand current issues of land degradation (Figure 5.6). The simplest indicator of potential for accelerated erosion is a map of the ratio of current to pre-European potential erosion (Figure 5.7).

The gross pattern of contemporary soil erosion potential being higher, in the north, reflects the natural distribution of soil erosion across the continent. Within each climatic zone, areas of significantly accelerated erosion potential have occurred—shown by the ratio of present to pre-European potential (Figure 5.7). These are areas where cover has been reduced at least seasonally. While the overall erosion rate is low in the cereal belt of Western Australia, it is still many times higher than the naturally very low rate. Similar results were found for the cropping belt from Victoria through to Queensland and the extensive grazing lands and tropical crop lands of north Queensland. On average, sheetwash erosion has accelerated by three times the natural rate.

Figure 5.6 Predicted pre-European mean annual sheetwash and rill soil erosion rate.

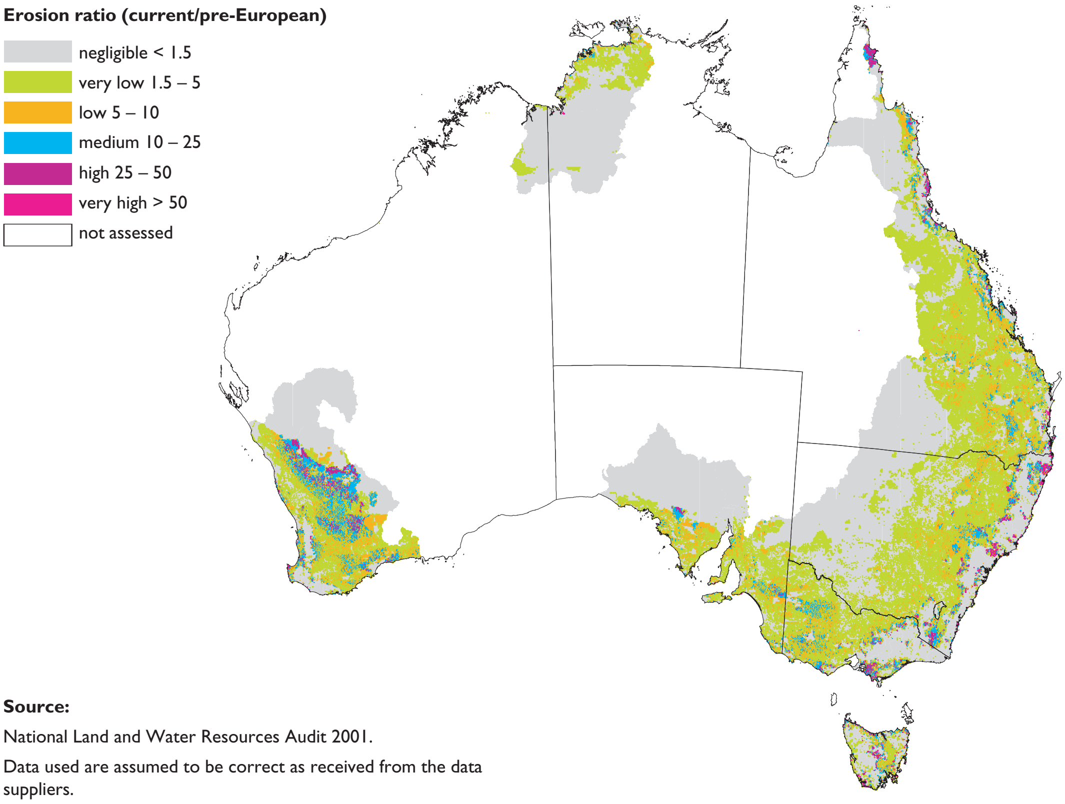


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 5.7 Present to pre-European sheetwash and rill erosion ratio.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Sheetwash in croplands

The most intensive cropping land uses have the greatest potential to cause accelerated erosion (Table 5.2). Crop lands make up only 8% of the assessment area. Sugar cane and tropical fruit crops are of particular concern, as they are located in areas of high rainfall erosivity. Where they occur on sloping land, soil erosion can only be stopped by retaining good cover at all times. Cereal and legume crops in southern Australia are less susceptible to accelerated erosion because of low rainfall during times of low cover.

Considerable effort to reduce soil erosion potential in croplands includes minimum tillage, stubble retention and contour banking—practices that are widely, but not universally, adopted. The sugar cane industry reports 80% adoption of minimum tillage, green cane harvesting and trash blanketing, reducing soil erosion rates on sloping land from the order of 100 t/ha/yr to 5–10 t/ha/yr. Tillage is still necessary when planting a new crop, creating a risk of accelerated soil erosion at these times.

Riparian filter strips offer a last line of defence to soil erosion—protecting streams from sediment and attached nutrients lost from farm land. Attention has only recently been given to riparian management as a means of mitigating against the impacts of some crop land use practices. Filter strips of less than 5 m width can be effective in protecting against erosion rates of less than 20 t/ha (Prosser & Karssies 2001).

Table 5.2 Summary of erosion by land use for river basins containing intensive agriculture.

Land use	Area (km^2)	Total erosion (t/yr)	Erosion rate with no conservation practice (t/ha/yr)	Rate of acceleration	Erosion rate* under best practice (t/ha/yr)
Closed forest	22 000	2 552 000	1	1	N/A
Open forest	228 000	6 900 000	<1	1	<1
Woodland (unmanaged lands)	220 000	103 400 000	5	3	N/A
Commercial native forest production	153 000	5 800 000	<1	1	<1
National parks	86 000	76 200 000	9	1	N/A
Cereals excluding rice	180 000	38 933 000	2	10	<1
Legumes	22 000	740 000	<1	3	
Oilseeds	6 000	2 382 000	4	10	
Rice	1 500	115 000	1	6	
Cotton	4 000	2 784 000	7	11	
Sugar cane	5 000	18 623 000	40	57	5
Other agricultural land use	2 000	2 329 000	54	34	~2
Improved pastures	190 000	41 429 000	2	5	N/A
Residual/native pastures	1 673 500	957 939 000	6	3	N/A
Total area of river basins containing intensive agriculture	2 793 000	1 260 126 000**	5		

*	Indicative values obtained from erosion plot studies where available.
N/A	Not applicable
**	It was predicted that on average there is a potential for about 4.8 billion tonnes of soil to be moved by sheetwash and rill erosion across the Australian continent each year.

Sheetwash in grazing lands

Grazing is the main land use contributing to total soil erosion across assessed river basins, because of the vast areas involved and their location in northern Australia (Table 5.2). Grazed land makes up 75% of the assessment area and is composed of woodlands as well as pastures—the basis of the beef industry in northern Australia. It is predicted that erosion under pasture lands has doubled from natural conditions, with a five-fold increase for improved pastures. Soil erosion under woodlands and native pastures contributes 86% of total assessed area.

Sheetwash erosion is much harder to manage in grazing than in cropping areas because of the:

- greater area;
- lower levels of inputs; and
- smaller marginal returns on investment.

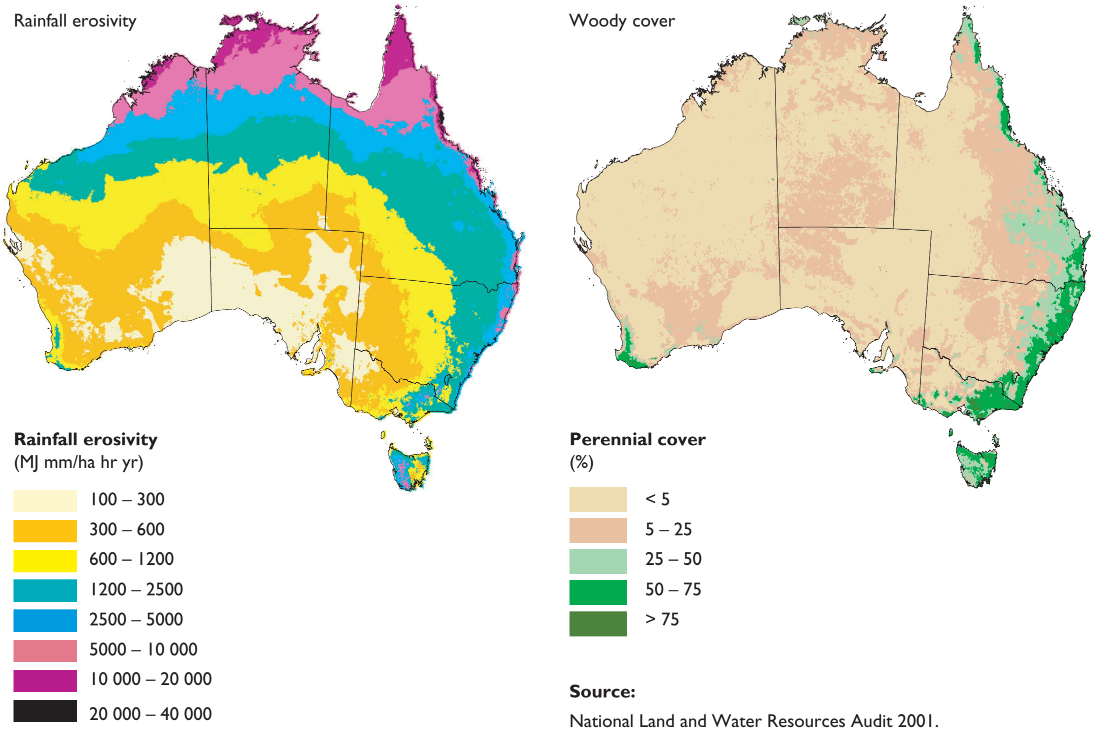
Structural works and other soil conservation practices are usually impractical in these areas. The greatest scope for reducing soil loss is through improved pasture and stock management aimed at maintaining adequate ground cover *at all times* (including drought planning, off-stream watering, cell grazing and management of pasture species). These issues are of greatest importance in the northern grazing lands where river suspended sediment loads have most increased and where sediment delivery to the coast is more likely.

Factors contributing to sheetwash and rill erosion

Maps of factors contributing to soil erosion potential illustrate how national patterns were derived (Figure 5.8).

- *Rainfall erosivity* refers to the erosive energy of rain, a function of the total amount of rainfall and its intensity in a typical storm. It varies very strongly across Australia and is highest in coastal regions of northern Australia.
- *Vegetation cover* strongly influences erosion potential—as perennial plant cover changes away from the coast, so too does erosion potential.
- *Slope length and gradient* vary less strongly. The effect of steep slopes along the east coast and in Tasmania on erosion potential is mitigated by good vegetation cover.
- *Soil erodibility* is a measure of the susceptibility of the soil to erode. It is a function of its structural stability and its capacity to absorb rainfall and minimise runoff. Comparing the soil erodibility factor with the soils map of Australia, heavy clay soils (Vertosols) and structurally unstable, chemically dispersible sodic soils (Sodosols) are highly erodible. Rocky soils (Rudosols) and weakly developed soils (Tenosols) are least erodible. Soils with high organic matter content are less erodible than those with low organic matter content. Much of the soils in south-west Western Australia, coastal south-east Australia and Tasmania are less susceptible to water erosion.

Figure 5.8 Factors contributing to sheetwash and rill erosion.

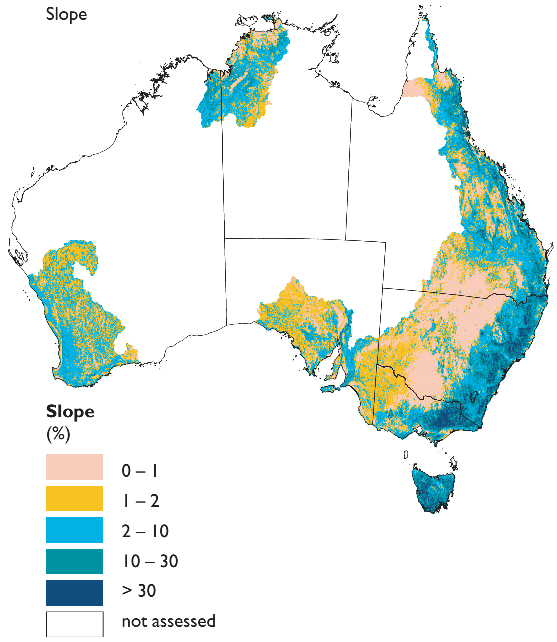


Source:

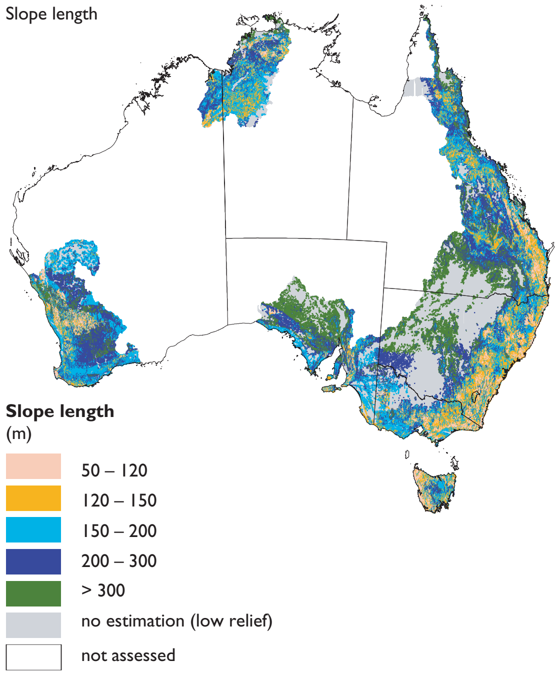
National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

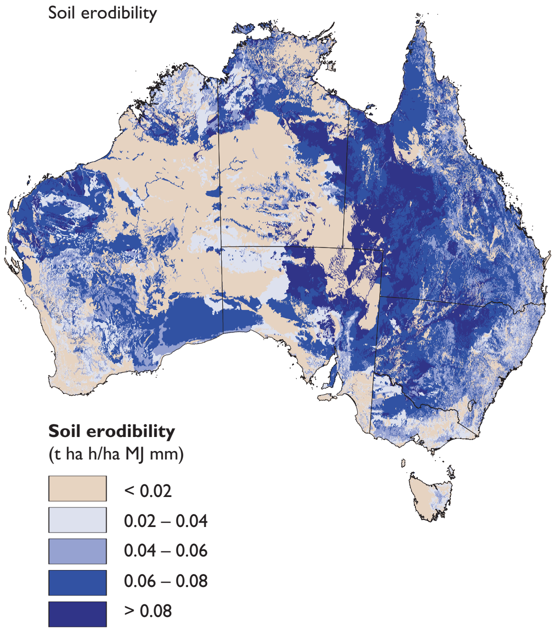
Slope



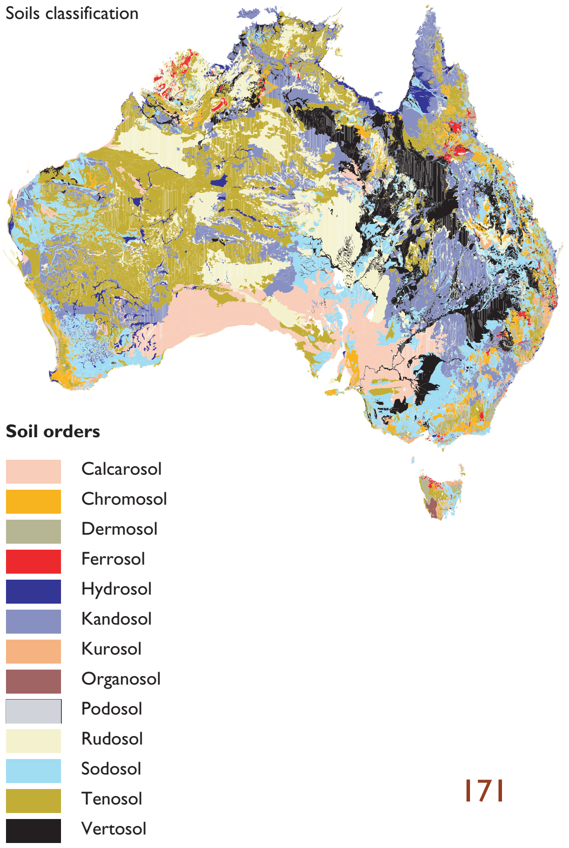
Slope length



Soil erodibility



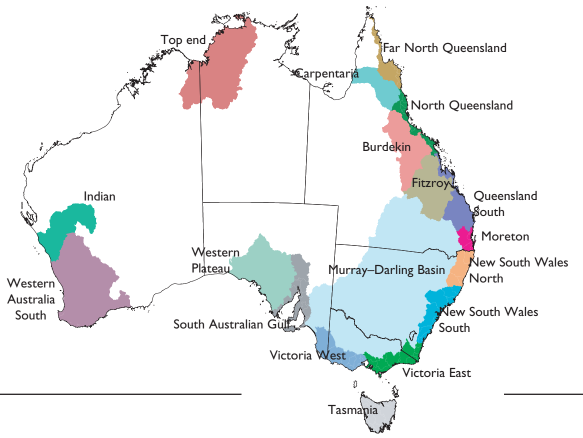
Soils classification



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.



GULLY EROSION

Gully erosion is a natural process. Prior to European settlement gullies eroded episodically for a hundred years or so, every few thousand years, and in a few valleys at any one time. The current extent of erosion up valleys is also considerably longer than occurred naturally. The current extensive and relatively synchronous erosion of many valleys is unprecedented for at least the last 15 000 years.

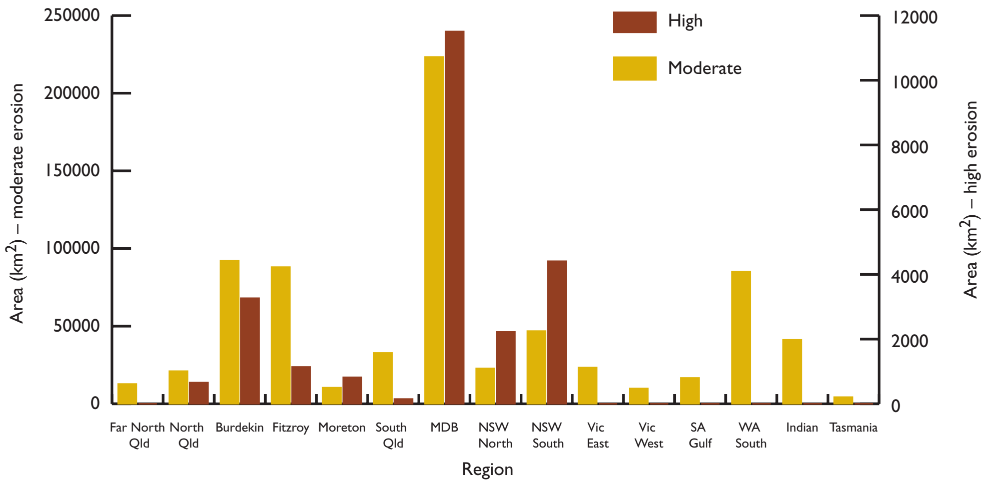
Many of the gullies of today's agricultural landscapes were formed soon after clearing of native vegetation and have since stabilised. They continue to produce poor quality run-off but have ceased to be a major erosion problem, despite considerable lengths of bare, steep banks. Such banks are not good indicators of active erosion, which is better detected by observing changes to gully position over time.

Average gully density within the assessment area was 0.13 km/km^2. This includes an approximate total of 325 000 km, that on average had produced 44 million tonnes of sediment each year. It is estimated that gullies have eroded 4.4 billion tonnes of sediment since European settlement of Australia. In most cases, gullies are well connected to streams and rivers, so that the vast majority of the eroded sediment has been delivered into the river network.

The greatest on-site problem of gully erosion is its threat to fences, tracks, roads and buildings.

Amelioration of gully erosion can range from fencing out stock to revegetation, through structural works to stabilising a gully head, to filling the gully and constructing erosion control dams and grassed waterways. These works can range in cost from $2000 to $50 000 per kilometre of gully, depending upon the nature of works. To treat all gullies in the river basins of the assessment area, at an average cost of

Figure 5.9 Area of moderate and high gully density in each region river basin containing intensive agriculture.



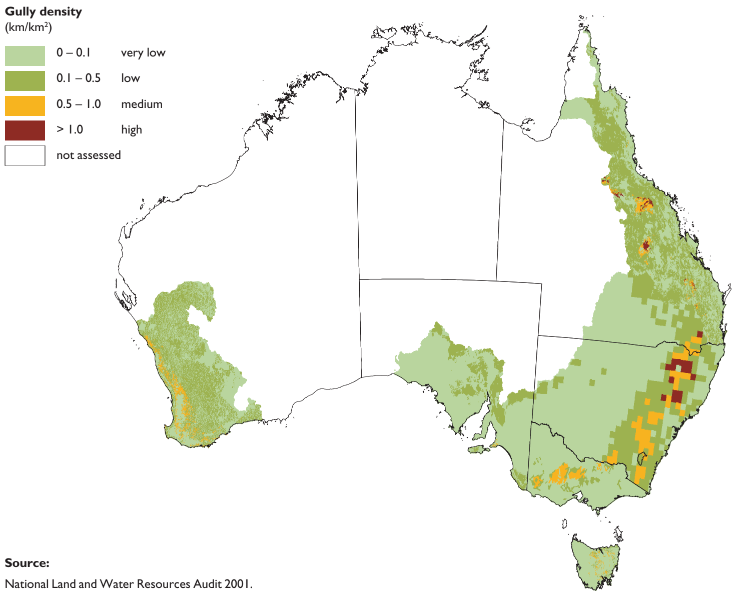
$20 000 per kilometre, would total $6500 m. Such resources are clearly not available, nor are they needed, for gullies naturally stabilise over time. Remedial works should be focused on those gullies that continue to erode and threaten structures, or those that yield considerable sediment or poor quality water. Local observations of gully movements and water quality measurements provide the information required to identify problem gullies.

- Moderate (0.1 – 1.0 km/km^2) to high (1.0 – 3.5 km/km^2) gully erosion occurs in an arc along the highlands and slopes of the Murray–Darling Basin (Table 5.3, Figure 5.10). Isolated areas of moderate to high gully density are also found in the Burdekin and Fitzroy River basins of Queensland.
- Extensive low to moderate density gully erosion occurs in south-west Western Australia (Figure 5.9). This is a significant erosion process for the region considering the low rates of surface wash erosion. Gully erosion commonly occurs on granitic or sandstone rock types, in areas of variable climate which produce seasonally low ground cover, and in rolling terrain of pastoral or mixed pastoral and cereal cropping land uses.
- Tasmania, and coastal areas of Queensland and Victoria have only localised gully erosion due to permanently high vegetation cover, and naturally well developed stream networks or broad valleys which dissipate run-off energy. Some areas of historical gully erosion—now covered by forests — are not represented in the map, because gullies could not be detected under forest cover. This applies mainly to alluvial gold mining in central Victoria and tin mining in Tasmania, where pockets of high gully density occur.
- The highest gully density* predicted was 3.0 – 3.5 km/km^2 in the Nogoa River sub-catchment of the Fitzroy River basin. Similar high values of gully density are possible for isolated areas in New South Wales and Victoria but were not detected because of averaging over large areas.

Table 5.3 Range of gully densities observed.

Erosion class	Gully density (km/km^2)	Mean annual sediment yield (t/ha/yr)
Low	< 0.1	<0.15
Medium	0.1 – 1	0.15 – 1.5
High	1 – 3.5	1.5 – 5.3

Figure 5.10 Gully density.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

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* Gully density can be converted into a soil erosion rate by considering the approximate age of a gully and the volume of soil removed to form the gully. An average gully is 5 m wide and 2 m deep. One kilometre of gully would then produce 10 000 cubic metres (approximately 15 000 tonnes) of sediment for each square kilometre of land. If that volume was eroded over an average gully age of 100 years, the mean annual rate of erosion would be 1.5 t/ha/yr.

STREAMBANK EROSION

Degradation of riparian vegetation is a major cause of streambank erosion, since it increases the susceptibility of streambanks to erode during floods:

- tree roots add substantial strength to streambanks, effectively preventing them from slumping and suffering other forms of collapse (even where streams have deepened or are undercut); and
- overhanging and emergent vegetation (e.g. *Phragmites*) is able to reduce flow velocities and the scouring of banks.

Four-fold increases to stream width and doubling of stream depth since European settlement is common along cleared creeks and rivers. This can be a significant source of sediment to the river, as well as, threatening valuable floodplain land and infrastructure.

Erosion of banks may not occur immediately following loss of riparian vegetation. Its intensity will also differ between rivers, and in some cases, large floods cause the majority of erosion (see box).

Variations in streambank erosion

Riparian vegetation in the Hunter River system on the New South Wales Coast was cleared late in the nineteenth century, a common practice throughout coastal New South Wales. Major erosion of streambanks did not occur until a sequence of large floods occurred in the 1950s. Floods between 1946 and 1955 caused an average 304 m of erosion along an 82 km stretch of the Hunter River (Erskine & Bell 1982).

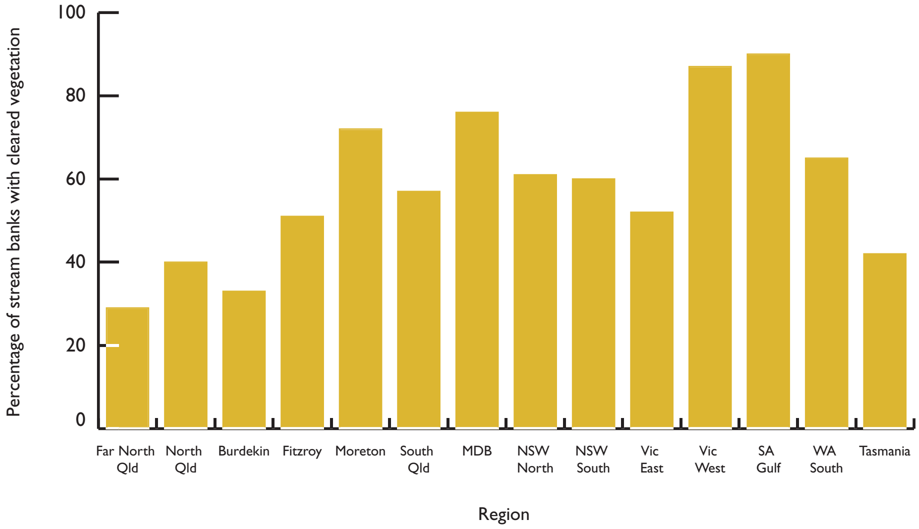
In higher energy rivers (e.g. the Bega River), cleared banks were capable of being eroded by even relatively small floods and channel widening occurred in the first few decades of clearing (Brooks & Brierley 1997).

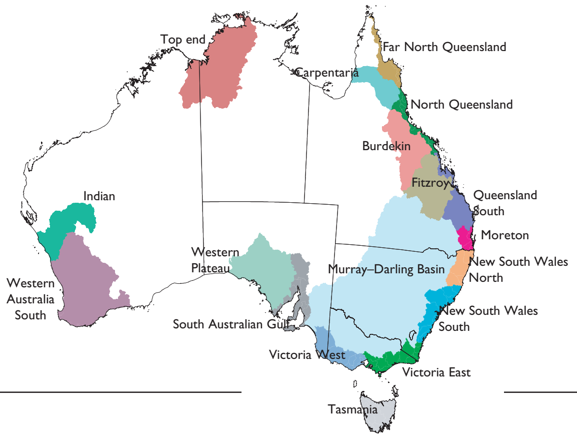
Rivers, such as the lower Lachlan River in central western New South Wales, are of such low energy that they have suffered relatively little erosion despite extensive clearing.

Mapping shows that across the assessment area, 65% of the river length has cleared riparian vegetation, including some 120 000 kilometres of cleared streams. Restoration of native vegetation requires $1.2 billion (at a conservative cost of $10 000 per kilometre for fencing and replanting with volunteer labour). Such investment is not currently feasible and not all areas of cleared riparian lands will be a high priority for restoring degraded streams. However, effort is needed to strategically target restoration works prioritised at regional, State and national levels. Priority could be given to areas where bank erosion creates problems of sediment deposition or loss of land, and where riparian vegetation is limiting ecological health.

- Western Victoria and the South Australia gulf region were mapped as having the highest amount of clearing along streams (Figure 5.11). These are regions with extensive native grasslands rather than riparian forests, so the extent of clearing is probably over estimated.
- Regions with the greatest proportion of cleared vegetation were found in the more developed parts of Australia including Moreton, Murray–Darling Basin, the New South Wales coast and south-west Western Australia. The Murray–Darling Basin is of particular concern because it represents 40% of the area assessed, while Moreton Bay is an area with a large open estuary, where increased supply of sediment from the catchment has been identified as a significant problem.

Figure 5.11 Estimated proportion of native vegetation removed along stream banks in river basins with intensive agriculture.





SEDIMENT DELIVERY TO STREAMS

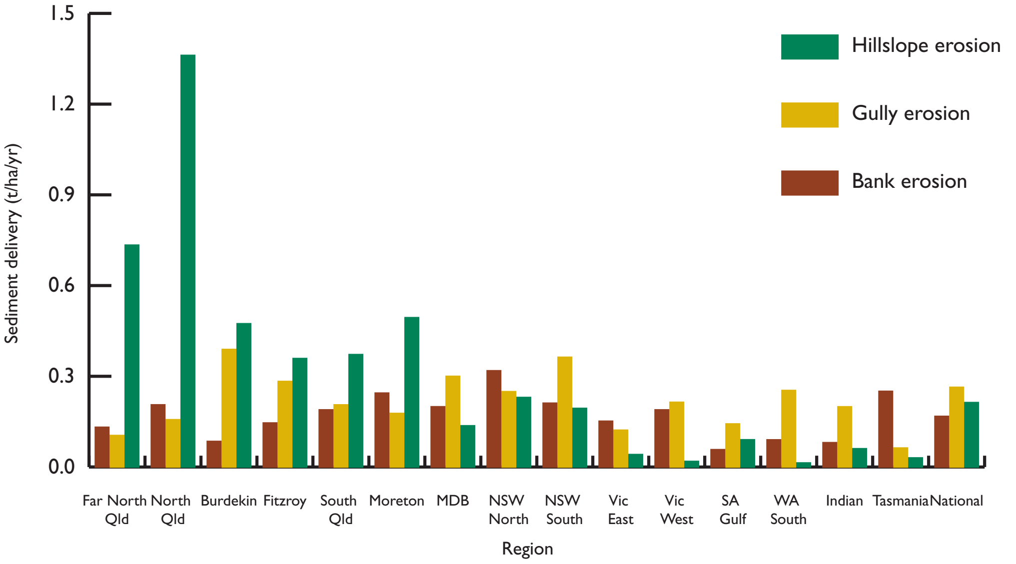
Sheetwash erosion, gully and streambank erosion all supply sediment to river networks. River sediment budgets were constructed to route this sediment through each river basin accounting for deposition and calculating net export. Table 5.4 summarises these terms across the assessment area.

Table 5.4 Components of sediment supply (million tonnes per year).

Gross sheetwash and rill erosion	666*
Delivery to stream from sheetwash and rill erosion	50
Gully erosion	44
Streambank erosion	33
Total sediment supplied to rivers	**127**
Total suspended sediment stored	66
Total bed sediment stored	36
Sediment exported from rivers	25
Total of stores and losses	127

Sheetwash and rill erosion dominate total erosion processes, but modelling estimates indicate that less than 8% of soil moving from hillslopes reaches the stream. Field measurements of differences between erosion measured on small plots to that measured at the scale of small catchments and whole hillslopes (Edwards 1993) indicate that much of this soil is deposited a relatively short distance downslope. Sediment delivery from gully and streambank erosion are of comparable magnitude to that from modelled estimates of sheetwash and rill erosion. The certainty of these predictions decreases from sheetwash and rill erosion through gully erosion to streambank erosion. They have enough certainty to demonstrate that each process needs to be considered in regional assessments of river sediment loads.

Figure 5.12 Estimated amounts of sediment supplied to streams from each erosion process.



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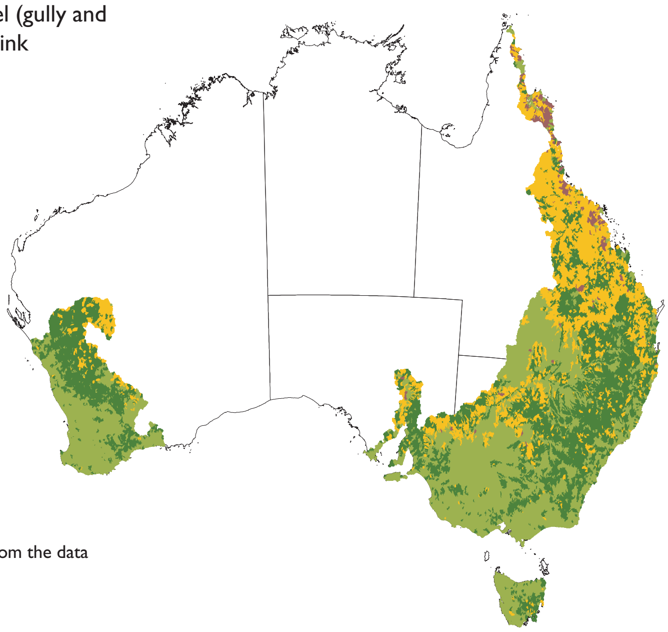
* Does not include sheetwash and rill erosion estimates for the Gulf, Western Plateau or Northern Territory as river budget assessments were not undertaken in these areas.

Strong regional differences in dominant sediment source occur across Australia (Figure 5.12):

- sheetwash and rill erosion are the dominant sources in Queensland river basins; and
- further south, gully erosion and streambank sources dominate, because lower rates of sheetwash and rill erosion exist. The predicted dominance of gully and streambank sediment sources over sheetwash and rill erosion in southern Australia is supported by field based sediment budgets for some catchments and by radionuclide studies which distinguish between surface and subsurface sources of sediment (e.g. Wallbrink et al. 1998).

Patterns within these regions (Figure 5.13) also show that gully erosion processes dominate in the drier parts of Queensland.

Figure 5.13 Ratio of hillslope to channel (gully and streambank) sediment sources by river link subcatchments.



Relative sediment sources (sheetwash and rill erosion/gully and bank erosion)

🟩 0 – 0.1
🟩 0.1 – 1.0
🟨 1.0 – 10.0
🟥 > 10.0
☐ not assessed

Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

The strong regional differences between sediment sources are significant. Techniques to prevent gully and streambank erosion are quite different to those applied to sheetwash and rill erosion:

- management of stream bank and gully erosion focuses on stock exclusion around streams, riparian revegetation and structural works; and
- sheetwash and rill erosion are ameliorated through cover management, tillage practices, contour banks, farm dams and filter strips.

Only 20% of the total load supplied to rivers is actually exported from rivers (Table 5.4). The remainder is deposited within the rivers, on floodplains or in reservoirs. This highlights the importance of assessing river loads for patterns of deposition in order to appropriately target management strategies. For bedloads, it is the sites of deposition that produce the downstream impacts of accelerated erosion.

THE FITZROY BASIN

A Queensland region dealing with soil erosion

The Fitzroy regional case study highlights land management, soil erosion and capacity for change within the grazing industry. Regional development plans need to include options for soil management to improve or maintain ecosystem health while taking into account the social and economic needs, and motivation and capacity of rural industries and other natural resource management stakeholders to implement these options.

Profile of the Fitzroy

- The Fitzroy Basin is the largest river basin draining the east coast of Australia. It is made up of six major catchments (Nogoa, Comet, Isaac-Connors, Mackenzie, Dawson and Fitzroy rivers), totalling 14.3 million hectares.
- The climate is subtropical and semi-arid, with high rainfall variability. A major challenge in this region is to maintain enough ground cover to minimise erosion of surface soil following very intense rainfall, and to control run-off following droughts, when vegetation cover is minimal.
- Fitzroy contains 10% of Queensland's agricultural land. Major land uses include cattle grazing (82% of land), irrigated cotton and dryland cropping (7%), forests and parks (9%), and mining (1%).
- Land use has changed significantly over the past few decades—extensive clearing of brigalow has provided large areas for grazing and broadacre cropping; new dams have increased irrigation.
- Opportunities for land use change will probably need development of sustainable and viable land and water management plans, and assessments of the capacity of communities to adjust and implement responsible decisions.
- Concern for catchment, river and estuarine health and possible impacts on the Great Barrier Reef Marine Park has been associated with these changes.
- Work at the Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management has noted some marked geomorphologic changes at the mouth of the Fitzroy River over the last fifty years.

Soil erosion in the Fitzroy: national context

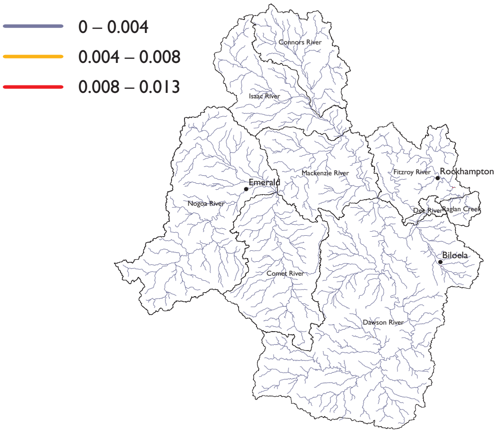
The Fitzroy Basin covers approximately 14 million hectares and makes up 8.5% of the national Audit assessment area. Sheetwash (62%) and rill erosion (24%) processes dominate gully and river bank erosion (12%); nationally, 40% of sediment is delivered to streams from hillslope erosion, 34% from gully erosion and 26% from streambank erosion.

The Fitzroy Basin is responsible for 20% of all sediment delivered from hillslopes to streams nationally. Of the 21 million tonnes of fine sediment reaching the coast nationally, 12% (2.6 million tonnes) come from the Fitzroy Basin, and the area has a specific sediment yield of 0.18 t/ha/yr, slightly higher than the national average. Fine sediment loads in the Fitzroy Basin are predicted to have increased 15 times above the natural rate since European settlement, which is well below the national average of 100 times the natural rate.

Gully erosion contributes 0.28 t/ha/yr to streams (national average is 0.26 t/ha/yr). There are significant areas of low to moderate gully density, with 62% of the basin having a gully density of 0.1 to 1 km per km^2, compared with the national figure of 37%. A small area of very high gully density (3 to 3.5 km per km^2) occurs in the Nogoa Catchment. Gully erosion is not considered a great concern for the Fitzroy Basin (<1% of the basin falls into the category of high gully density).

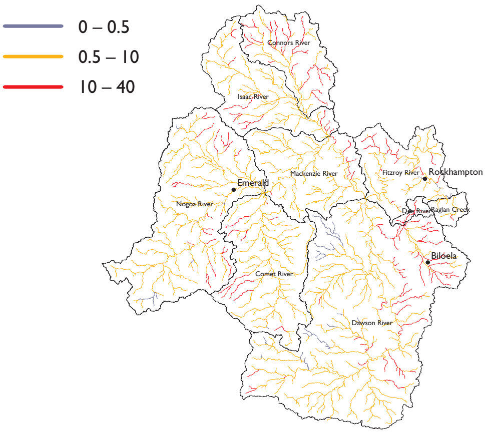
Around 15% of sediment in the Fitzroy Basin is derived from streambank erosion, a natural process which is accelerated in areas of degraded riparian and streambank vegetation and poor stability. The Fitzroy Basin contains 15 500 km of streams, of which around 50% have degraded riparian vegetation (just below the national average). All coarse sediment eroded through gully and river bank erosion remains deposited in downstream tributaries leading to 13% of the river network with in-stream sediment deposition greater than 30 cm (poor in terms of river health but lower than the national average of 16.5%).

While higher loads of fine sediment may arise from cropped lands, erosion management needs to focus on maintaining surface cover on land used both for cropping and grazing.



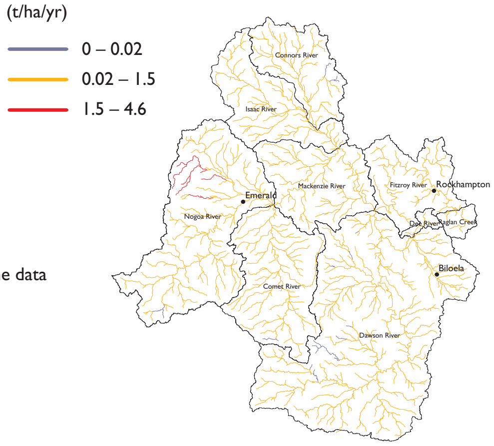
Annual sediment load from bank erosion

(t/ha/yr)



Annual sediment load from hillslope erosion

(t/ha/yr)



Annual sediment load from gully erosion

(t/ha/yr)

Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Table 5.5 Water-borne erosion: Fitzroy in context.

Attribute	National*	Fitzroy basin	Fitzroy as % of national
Area (million ha)	167	14	8.5
Stream length ('000 km)	181.5	15.5	8.5
Sediment sources			
Bank erosion (Mt/yr)	33	2	6.0
Gully erosion (Mt/yr)	44	4	9.0
Hillslope erosion (Mt/yr)	50	10	20.0
Total (Mt/yr)	127	16	12.5
Sediment delivery to coast	21 Mt/yr 0.13 t/ha/yr	2.6 Mt/yr 0.18 t/ha/yr	12
In-stream sedimentation >30 cm			
Stream length ('000 km)	30 000	2 000	6.5
Percentage of total	16.5%	12%	
Degraded riparian vegetation			
Stream length ('000 km)	118 600	7 800	6.5
Percentage of total	65%	50%	

* The erosion assessment was undertaken for river basins containing intensive agriculture.

DEPOSITION ON RIVER BEDS

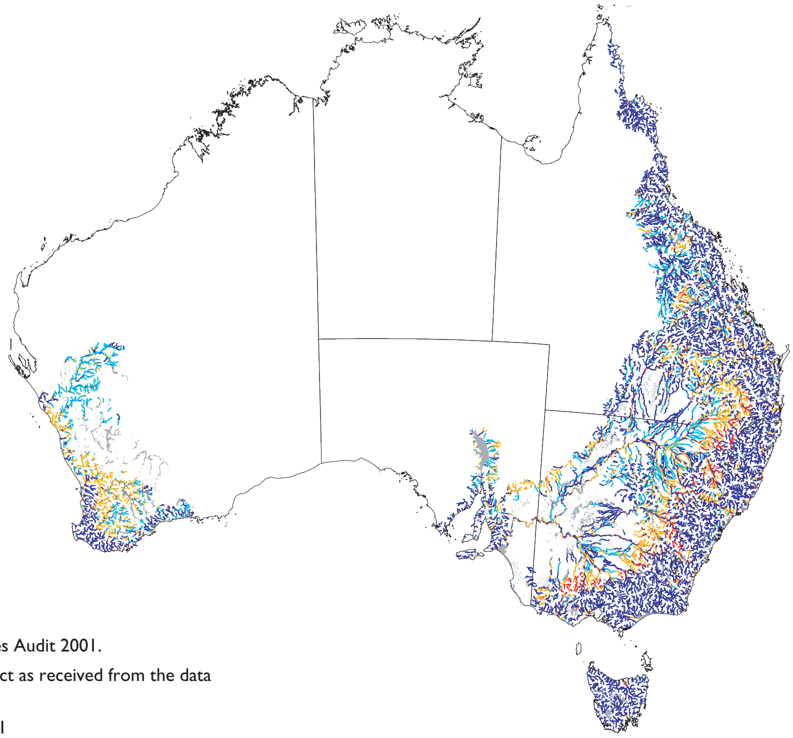
Accumulation of sands and gravels on river beds since European settlement of Australia is a major issue for river health.

Many coastal streams of Australia have beds of stones (cobbles), boulders and rock outcrop that are ideal habitat for benthic algae, macroinvertebrates and some fish species. Scour pools and undercut banks, or pools surrounding fallen debris also occur and are important refugia and breeding areas for fish and other biota. Fine sediment and nutrients that accumulate between the rocks or in the deep pools during low flows, are periodically flushed out, cleaning out accumulated debris and re-initiating surfaces for fresh colonisation by algae.

Where the supply of sands and gravels from upstream exceed a river's flushing capacity, this material starts to accumulate covering the rocky surfaces and filling deep pools. The sand and gravel are too unstable for growth of benthic algae and loss of deep pools also means a loss of refugia and breeding grounds. In the most extreme example of deposition, the bed of the river becomes an inhospitable flat sheet of dry sand during low flow.

The semi-arid areas of northern Australia and the western Murray–Darling Basin have naturally sandy river beds as a result of the climate, natural erosion processes and low slopes which result in sand supply exceeding capacity. It should not be assumed that these are impacted streams and the predictions suggest that they have suffered little net accumulation of sand.

Figure 5.14 River bed sediment accumulation.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Extensive deposition occurs in reaches immediately downstream from areas of high gully and streambank erosion (Figure 5.14).

- Extensive deposition occurs in the arc of the eastern boundary of the Murray–Darling Basin and parts of the Burdekin and Fitzroy basins.
- Coastal streams to the south and east of the Murray–Darling Basin are less impacted because of their higher gradients and discharges.
- The Bega, Hunter and Glenelg rivers are also affected.
- High energy rivers (e.g. across much of coastal north Queensland and Tasmania) have little historical accumulation of sand.
- Rivers in much of Western Australia have low gradients and insufficient energy to carry increased sediment loads, even though rates of sediment supply are not high.

There are 30 000 km of stream in the assessment area predicted to be impacted by sediment accumulation of greater than 0.3 m since European settlement.

- Western Australia South and the Murray–Darling Basin are the worst affected areas with 30% and 21% of streams affected by stream accumulation respectively.

This assessment only includes streams affected by supply of sand from gully and streambank erosion. Another significant source of debris is from alluvial mining for gold or tin, or from the supply of mine tailings to rivers (e.g. in the Ringarooma, George, King, Queen and South Esk rivers in Tasmania; the Tambo River, Ovens River, Yackandandah Creek and Bendigo area in Victoria; the Rocky and Molongolo rivers in New South Wales; and Magela Creek in the Northern Territory).

This assessment presents a snapshot of the current situation. The accumulation is really a pulse of material that will gradually move through the system over time driven by slow movement of sand during flood events. This means that even if source erosion was stopped today, large areas of sand deposition would continue to progress through river systems. Much of the sediment deposited in the upper tributaries of the Murray–Darling Basin was delivered to streams by erosion in the late nineteenth and early twentieth centuries. The sediment will continue to have impacts unless stabilised, extracted or flushed.

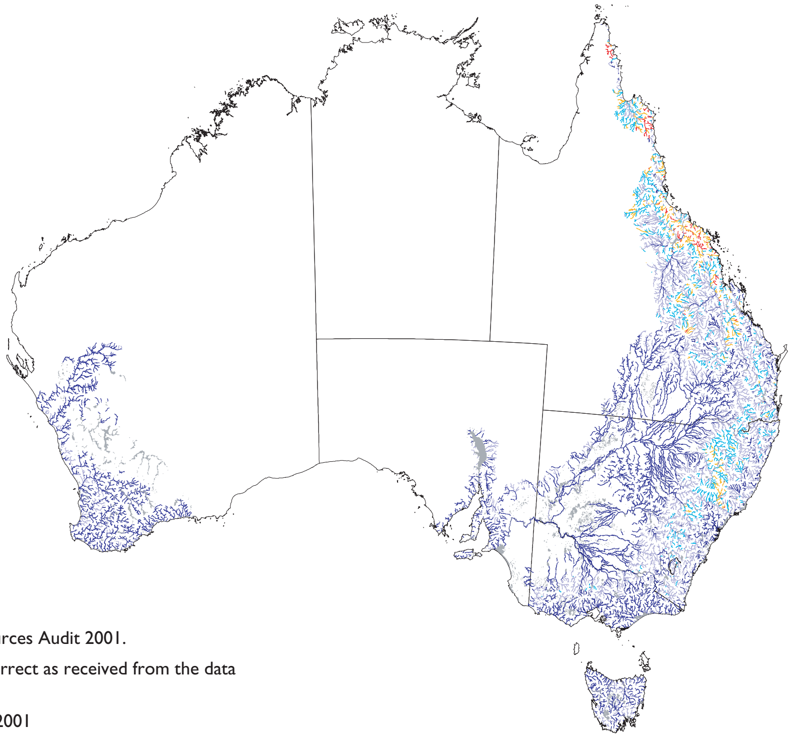
SUSPENDED SEDIMENT LOADS

Suspended sediments, mainly clay and silt particles, impact on streams by:

- covering surfaces;
- decreasing light availability; and
- carrying increased loads of nitrogen and phosphorus.

The mean annual yield of suspended sediment (Figure 5.15) is lower in southern Australia than northern Australia—reflecting lower erosion rates in the south. Within a river basin, suspended sediment loads grow as catchment area increases. Displaying loads per unit area (e.g. tonnes/hectare/year) removes this effect and shows where high mean annual loads exist.

Figure 5.15 Mean annual suspended sediment yield per hectare of catchment.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

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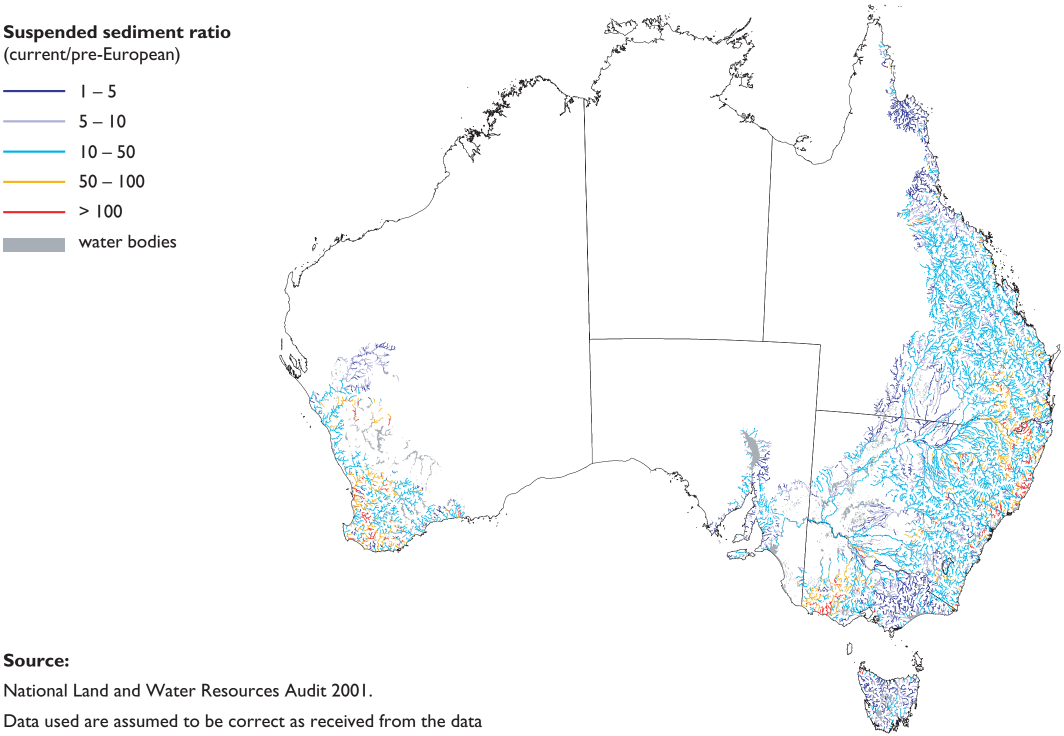
- The highest absolute suspended sediment loads were from the Fitzroy and Burdekin Rivers which each delivered around 3 million tonnes/year to the coast. These are large catchments with significant erosion, both natural and accelerated. Floodplain deposition is limited and there are relatively few large dams to trap sediment.
- Catchments which exported over 1 million tonnes/year are the Murray–Darling Basin, and the Normanby, Hunter and Burnett Rivers. The Murray–Darling Basin has an area nearly five times larger than the Fitzroy basin, but a lower sediment yield. There are high areas of suspended load areas in the headwaters of the Murray–Darling Basin, but on average, the erosion rate is lower. There are also substantial lowland floodplains in the Murray–Darling Basin, and many reservoirs that prevent most of the sediment from reaching the coast. The issue in the Murray–Darling Basin is redistribution of sediment not export to the coast.
- Regions of low erosion rate (e.g. south-west Western Australia, coastal Victoria, Tasmania and South Australia) had low sediment loads, regardless of deposition potential.

Figure 5.16 Ratio of current suspended load to pre-European suspended load.



Source:

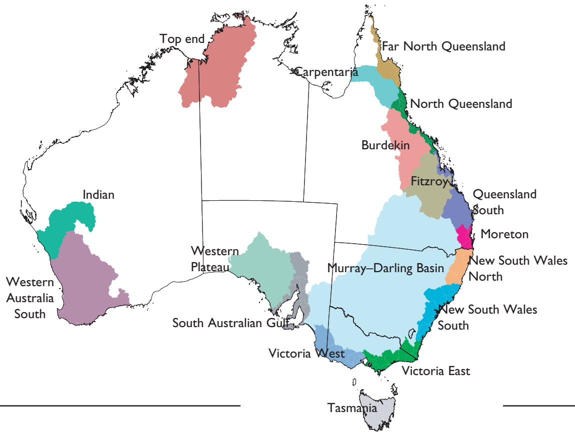
National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

River discharge was not directly used to predict sediment loads and any such correlations are coincidental. Rivers can carry as much suspended sediment as is supplied, so there is no physical reason why rivers with high discharges have high sediment load (e.g. the Murray River has a similar mean annual flow to the Burdekin River, yet the Burdekin River yields three times more sediment).

Naturally strong differences occur across Australia in soil erosion and these are expected to be reflected in river sediment loads. It is also reasonable to expect that local ecosystems adjust to these loads. Loads of suspended sediment can be expressed as a ratio of the predicted natural suspended loads (Figure 5.16). The natural suspended load (pre-European) is an estimate of sheetwash and rill erosion based on the assumption that there was negligible bank and gully erosion under pre-European conditions.

- Some 12% of the river basins in the assessment area had suspended sediment loads more than 50 times the pre-European loads. Such inflated loads are supported by measurements in south-eastern Australia, where sediments loads have increased by between 4 and 400 times since European settlement (Wasson 1994).
- Map predictions show that the present suspended sediment yields in south-west Western Australia are commonly between 50 and 100 times greater than the pre-European rate. This results from the very low natural erosion rate, so that even low magnitudes of streambank and gully erosion inflate sediment yields.
- Other areas of large increases in load are the Dundas Tableland the eastern part of the Murray–Darling Basin and coastal New South Wales and Queensland as far north as the Herbert River.
- Areas of low impact include much of Tasmania, north-eastern Victoria and far north Queensland. All of the areas of inflated sediment loads are ones of potential concern over ecological impacts on rivers, floodplains and estuaries. While suspended sediment impacts on freshwater ecosystems are not widely demonstrated, the assessment suggests that they cannot be dismissed over much of agricultural Australia.



SEDIMENT EXPORT FROM RIVERS

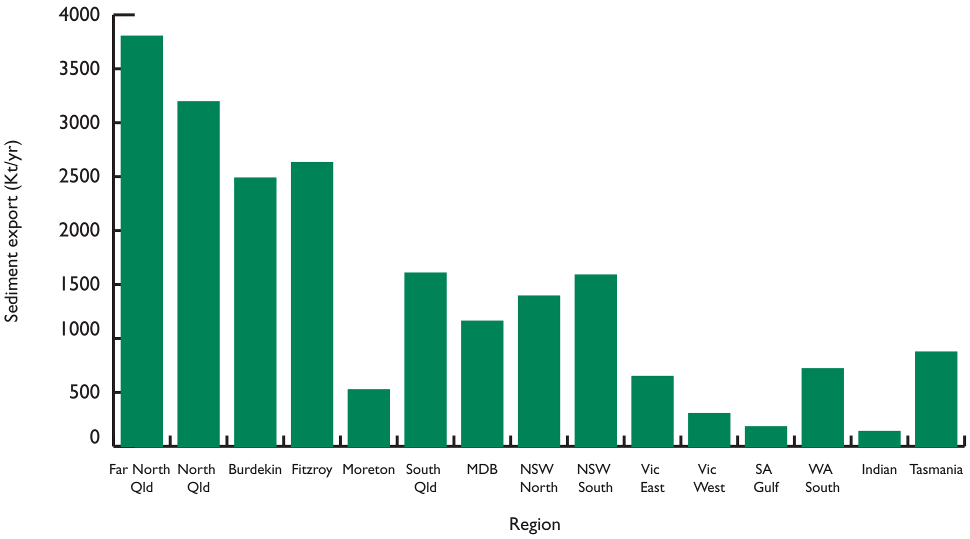
Sediments from rivers are eventually deposited in estuaries and inshore marine environments. Increased rates of deposition can:

- smother ecologically important habitats such as seagrass beds; and
- supply nutrients to and change the food web structure of an estuary.

Only 20% of sediment delivered to streams in the assessment area were predicted to actually reach estuaries, so it cannot be concluded that increased erosion from a catchment necessarily results in significantly increased sediment export to an estuary or the coast. Erosion from upstream requires efficient delivery of the sediment through the river network to link to an estuary. In many of the bigger catchments, the sediment source is hundreds of kilometres from the coast and has many opportunities for deposition onto floodplains or into reservoirs.

- Sediment exported from rivers is a major concern in Queensland rivers, because of the high loads exported (Figure 5.17) into significant marine environments. Sediment export is natural in this region (demonstrated by the relatively unimpacted Normanby River basin), but many of the basins further south have suspended sediment loads that are 5 to 15 times the natural level.
- Rivers on the New South Wales coast export significant quantities of sediments.
- Export of sediments is relatively low for much of the remaining coast.

Figure 5.17 Mean annual sediment export from rivers in each region.



The origin of the sediment in large coastal catchments is of greater importance than the actual export rate. The assessment traced the sediment load of each river reaching the coast to determine which were the contributing subcatchments (expressed as sediment loss [tonnes/ha/year]). Subcatchments making substantial export contributions to the coast are those with high erosion and limited deposition potential between the source and sea—subcatchments close to the coast are more likely to contribute to the coastal yield (Figure 5.18).

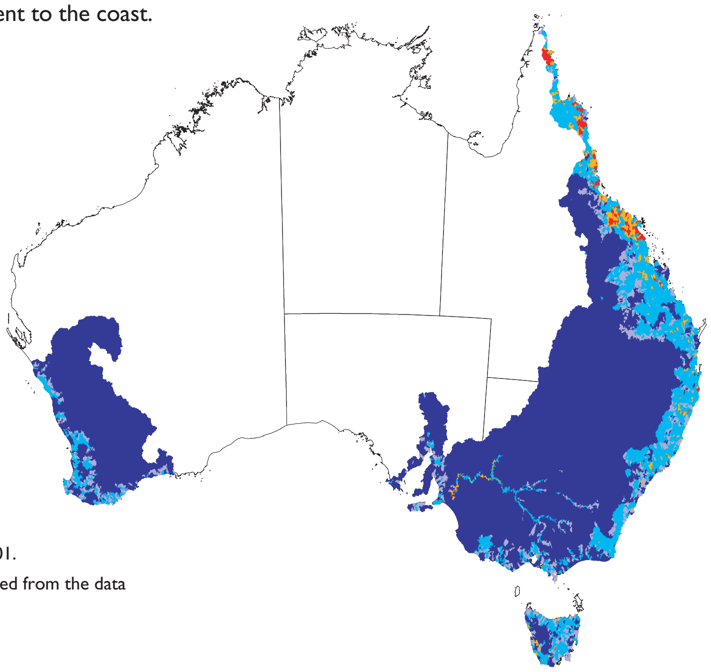
- Sediment is derived from inland areas in catchments (e.g. the Fitzroy) where there are significant sources inland and where rivers have relatively high energy and are confined, which engenders efficient delivery of sediment to the coast. In these catchments, there is a very strong relationship between actions undertaken on the ground at farm scale and impacts on coastal systems.
- Subcatchments of the Murray–Darling Basin deliver very little sediment to the coast because the areas of high erosion are in the headwaters over a thousand kilometres from the mouth, with extensive lowland floodplains and large reservoirs along the route.

Ninety percent of sediment exported from rivers comes from only 20% of the contributing catchment area. While soil erosion is a widespread issue across the assessment area, targeted management can be used to address specific problems. If the goal is to reduce sediment exports from rivers then remedial works can be focused on particular sediment sources, and the land uses and erosion processes found there. Relatively little attention is needed for the rest of the catchment. Sediment delivery to the coast is not the only concern and the same principles can be applied where a reduction in sediment delivery to particular reservoirs, lakes or individual river reaches of high value is required.

Figure 5.18 Contribution of sediment to the coast.

Contribution of sediment to the coast
(t/ha/yr)

- 🟦 0 – 0.05
- 🟪 0.05 – 0.1
- 🟦 0.1 – 1.0
- 🟧 1.0 – 2.0
- 🟥 > 2.0
- ☐ not assessed



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

IMPLICATIONS FOR AGRICULTURE

Water-borne soil erosion impacts on river, estuary and marine resources and is therefore a major issue for Australian agriculture and catchment management. It causes unsustainable losses of soil for agriculture that far exceed rates of soil development, by as much as 50 times in some areas.

Hillslope erosion (sheet and rill erosion) remains high in Australia's tropical northern regions during the wet season, and especially in the semi-arid woodlands and arid interior.

- *Maintaining vegetative cover, minimising soil disturbance and building sediment-trapping wetlands remain imperatives.*

In southern and eastern Australia, gully erosion, while inactive in many previously formed gullies, persists as the major erosion process affecting river condition. Sediment from these previously active gullies has affected about 10 000 km of stream length in the Murray–Darling Basin alone. These rivers, now with coarse sand accumulations in stream beds, exacerbate flooding and smother native fish habitat.

Active gully erosion is still occurring in northern Queensland and in south-western regions of Western Australia.

- *Changes to agricultural practices that minimise gully erosion is an imperative, both from an on-farm and off-farm perspective.*

River bank erosion is also a major problem. Extensive lengths (120 000 km) of riparian vegetation along eastern Australia's rivers and streams are degraded and require rehabilitation. Where these landscape resources are intact, they protect the integrity of banks against erosion. Priority areas include much of the Murray–Darling Basin, South Australia and south-western regions of Western Australia.

Sediment delivery to regional streams, rivers and marine estuaries remain high priorities in specific catchments. Deposition of sand and suspended sediments in streams and rivers is greatest in the Murray–Darling Basin, coastal regions of New South Wales, south-east Queensland and the Glenelg region of Victoria.

From a near-shore and estuary perspective, about 90% of suspended sediment loads reaching marine and estuarine environments are derived from 20% of agricultural catchments, particularly in coastal regions of Queensland and New South Wales. On an average annual basis about 25% or 12 million tonnes of sediment delivered to streams is discharged into the Great Barrier Reef lagoon. This is predicted to be approximately three times greater than the natural load, with consequent impacts on estuaries and marine fisheries, seagrasses and near-shore coral reefs.

National, State and regional priorities for natural resources management can now be re-appraised in the light of these findings. The effects on-farm are irreversible and impacts off-farm which will continue for many generations. Catchment management and industry priorities, particularly in terms of implementing improved practice are essential. Total impacts are likely to be equal to, if not greater than, those of dryland salinity. It is an imperative that soil management targets hillslope, gully and river bank erosion in the various regions of Australia. Management approaches will differ across Australia's catchments as processes that supply sediment to rivers also differ.

REFERENCES

Brooks A. & Brierley G. 1997, 'Geomorphic responses of lower Bega River to catchment disturbance, 1851-1926', *Geomorphology* vol. 18, pp. 291–304.

BRS, 2000, http://www.brs.gov.au:80/land&water/landcov/alcc_results.html

Edwards K. 1993, 'Soil erosion and conservation in Australia', in *World Soil Erosion and Conservation*, D. Pimental (ed.), Cambridge University Press, Cambridge.

Erskine W.D. & Bell, F.C. 1982, 'Rainfall, floods and river channel changes in the upper Hunter', *Australian Geographical Studies* vol. 20, pp. 183–196.

Ford G.W., Martin J.J., Rengasamy P., Boucher S.C. & Ellington A. 1993, 'Soil Sodicity in Victoria', *Australian Journal of Soil Research* vol. 31, pp. 869–909.

Gallant J. 2001, *Topographic scaling for the NLWRA sediment project*, CSIRO Land and Water Technical Report 27/01, Canberra.

Graham O.P. 1989, *Land degradation survey of NSW 1987-88: Methodology*, SCS Technical Report No. 7, Soil Conservation Service of NSW.

Hughes A.O., Prosser I.P., Stevenson J., Scott A., Lu H., Gallant J. & Moran C.J. (in press) 'Gully density mapping for Australian river basins', *Proceedings of the Third Australian Stream Management Conference,* Cooperative Research Centre for Catchment Hydrology, Melbourne.

Jeffrey S.J., Carter J.O., Moodie K.B. & Beswick A.R. (2001), 'Using spatial interpolation to construct a comprehensive archive of Australian climate data', *Environmental Modelling and Software* vol. 16 pp. 309–330.

Jones M-A. 2000, *Technical Report 3 -Theme7-Catchment Health-Fitzroy Implementation Project, Queensland.* Queensland Department of Natural Resources.

Karssies L. & Prosser I.P. 2001, 'Designing grass filter strips to trap sediment and attached nutrient', in I. Rutherford, F. Sheldon, G. Brierly & C. Kenyon (eds), *Third Australian Stream Management Conference*, Brisbane 27–29 August 2001, Cooperative Research Centre for Catchment Hydrology, Melbourne.

Lovett S. & Price P. (eds) 1999, *Riparian Land Management Technical Guidelines, Volume one: Principles of sound management*, LWRRDC, Canberra.

Lu H., Gallant J., Prosser I.P., Moran C., & Priestley G., 2001a, *Prediction of Sheet and Rill Erosion Over the Australian Continent, Incorporating Monthly Soil Loss Distribution*, Technical Report 13/01, CSIRO Land and Water, Canberra, Australia.

Lu H., Raupach M. & McVicar T. 2001b, 'A robust model to sperate remotely sended vegetation indices into woody and non-woody cover and its large scale application using AVHRR NDU2 Time Series', Technical Report 135/01, CSIRO Land and Water, Canberra, Australia.

Pickup G. & Marks A. 2001, *Identification of floodplains and estimation of floodplain flow velocities for sediment transport modelling*, NLWRA Sediment Project (CLW 12).

Prosser I.P., Hughes A.O., Rustomji P., Young W. & Moran C.J. 2001, *Assessment of River Sediment Budgets for the National Land and Water Resources Audit*, CSIRO Land and Water Technical Report (in press).

QDNR 2000, http://www.dnr.qld.gov.au/silo

Renard K.G., Foster G.A., Weesies D.K., McCool D.K. & Yoder D.C. 1997, *Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation*, Agriculture Handbook 703, United States Department of Agriculture, Washington DC.

Wallbrink P.J., Olley J.M., Murray A.S. & Olive L.J. 1998 'Determining sediment sources and transit times of suspended sediment in the Murrumbidgee River, NSW, Australia using fallout ^{137}Cs and ^{210}Pb' *Water Resources Research* vol. 34, pp. 879–887.

Wasson R.J. 1994 'Annual and decadal variation of sediment yield in Australia, and some global comparisons', *International Association of Hydrological Sciences Publication No. 224* , pp. 269–279.

Wischmeier W.H. & Smith D.D. 1978, *Predicting rainfall erosion losses: A guide to conservation planning*, US Department of Agriculture, Agriculture Handbook No. 537, US Government Printing Office, Washington, DC.

SUMMARY

Nutrient sources*

- Relative importance of different sources of nitrogen and phosphorus varies between river basins.
- The dominant sources of phosphorus (over 50%) are: hillslope erosion in Queensland and New South Wales; gully and river bank erosion, and dissolved phosphorus in run-off in coastal Victoria, South Australia, Western Australia and Tasmania; and in some basins urban point source discharges (e.g. 30% of the total load for Moreton Bay).
- Dissolved nitrogen in run-off makes up a greater proportion of the total load than dissolved phosphorus. Total nitrogen loads come mainly from hillslope erosion in Queensland and coastal New South Wales; contributions from hillslope erosion and dissolved nitrogen loads in run-off in the Murray–Darling Basin are comparable in magnitude; and over 60% of the total load occurs as dissolved run-off in coastal Victoria, South Australia, Tasmania and much of Western Australia.
- Management of nutrient exports will vary according to the relative dominance of nutrient sources.

Nutrient exports to receiving waters

- Total nutrient loads discharged from river basins are partly dictated by basin size—large basins export larger loads. Smaller basins can export large loads if they have high natural or induced export rates (e.g. due to steep slopes and intense rainfall; increases in population (sewage discharges) and changes in land use and management, such as intensive cropping on river flood plains).
- Efficiency of phosphorus delivery from rivers to the coast varies from as low as 3% in the Murray–Darling Basin to over 90% in Tasmania. Nitrogen deliveries vary from 14% for the Murray–Darling Basin to over 90% for Tasmania.
- The major sink for phosphorus and nitrogen is floodplain sedimentation, but reservoir sedimentation (for both nitrogen and phosphorus) and riverine denitrification (for nitrogen only) can account for significant proportions.

- Due to a lack of data, intensive rural industries (e.g. feedlots and piggeries) were not included. However it should be noted that these industries are subject to certification, specific industry guidelines, and are regulated and monitored through State government activities.

SUMMARY

- Nearly 19 000 tonnes of total phosphorus and 141 000 tonnes of total nitrogen are predicted to be exported down rivers to the coast each year from areas of intensive agriculture: highest exports occur in the Far North, northern Queensland, Moreton Bay and coastal New South Wales.

Changes in river nutrient loads

- Changes in nutrient load can indicate where important changes in water quality may have taken place. However, as nutrient loads in many rivers are dominated by storm events, changes in nutrient loads do not give a complete picture of the nutrient aspects of water quality.

- Annual total phosphorus loads in river networks averaged nearly 3 times higher than estimates for pre-European settlement levels. Average annual total nitrogen loads were estimated to be more than double pre-European settlement levels.

- In over 100 000 km of river (60% of river length assessed), total phosphorus loads had increased by more than 3.5 times, possibly resulting in substantial ecological changes. Total nitrogen loads increased by this amount in about 30% of the assessed river length.

- The greatest nutrient load impacts arising from catchment disturbances were predicted to be in the Burdekin, Murray–Darling, Murchison and Greenough basins.

INTRODUCTION

Increases in river nutrient loads generally lead to increases in the production of algae and aquatic plants, with follow-on effects up the aquatic food chain. Large nutrient increases typically favour a small number of species at the expense of others, and so while overall system productivity is increased, biodiversity is reduced. The reduced diversity of species is often associated with reduced system resilience, and catastrophic collapses are common. Such collapses may include the death and decay of large algal blooms, thereby increasing biological oxygen demand, lowering dissolved oxygen levels and leading to massive fish kills and high mortality amongst other river fauna (see *Australian Catchment, River and Estuary Assessment 2001* for the Audit river and estuary assessments).

River nutrient budgets for phosphorus and nitrogen allow determination of:

- major sources of nutrients to rivers;
- major loss pathways for nutrients transported through river systems; and
- magnitude of nutrient exported to estuaries and the coast.

They are linked to landscape nutrient budgets, because erosion and surface run-off are important pathways for nutrient loss from the landscape. An understanding of the fate of nutrients lost from landscapes and ecological responses to nutrient loads in the receiving waters, can help guide land and water planning and management.

A modelling approach was developed to combine outputs from erosion and river sediment transport modelling, with landscape–plant–soil–atmosphere–nutrient flux modelling and point source discharge data. River nutrient transport modelling considers dissolved nutrients that are associated with those bound to suspended sediments. Exchanges between these forms are modelled for phosphorus. Losses from transport include:

- fine sediment deposited in reservoirs and on floodplains; and
- denitrification of dissolved nitrogen to nitrogen gas.

MODELLING RIVER NUTRIENT TRANSPORT

Agricultural and urban disturbance within a catchment leads to increases in nutrients exported to the river systems. These increased nutrient loads affect river ecosystems, usually in undesirable ways. Assessing changes in nutrient loadings is therefore an important aspect for assessing river condition, and one that highlights the linkages between a river and its catchment.

Assessing river nutrient load is complex—either using measured data or by modelling—because of complex processes involved in nutrient sourcing and transport, and the highly time dependent variability of river flow. Process modelling is usually carried out in conjunction with detailed daily hydrology modelling. However, this is not required for broad-scale assessments of changes, and in any case sufficient data are often not available.

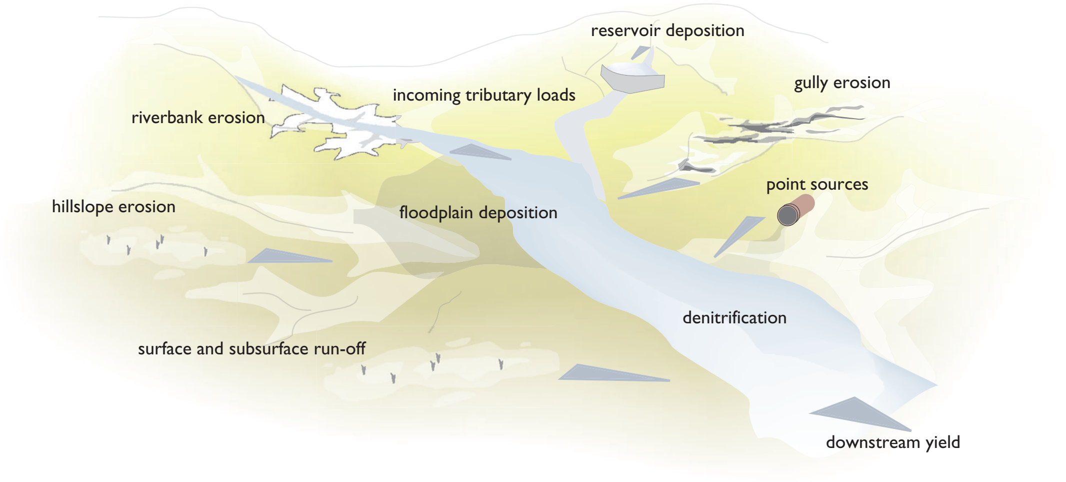
A model of river nutrient transport (Annual Network Nutrient Export—see box) was developed to predict current and pre-European nutrient loads in Australian rivers.

Losses of sediment-bound nutrients occur due to fine sediment deposition and long-term storage on floodplains and in reservoirs. These terms were estimated using the *Sed*iment river *Net*work (SedNet) model (Prosser et al. 2001) and assumed that:

- floodplain deposition accords to settling velocity theory; and
- reservoir deposition uses a modified 'Brune rule' (Brune 1953) that estimates the trap efficiency of a reservoir as a function of the storage capacity and the annual flow volume.

Nutrients not lost from transport by fine sediment deposition or denitrification are exported from the river network. As the Annual Network Nutrient Export model does not represent estuarine nutrient transport and transformations, 'exports' from the river network combines nutrient delivery to estuarine and near-shore marine environments.

Figure 6.1 Network link and 'internal' catchment area indicating the modelled nutrient sources and sinks.



ANNUAL NETWORK NUTRIENT EXPORT (ANNEX)

The model:

- Sums nutrient sources delivered to each link* of a river network, and accumulates the consequent loads to determine average annual exports.
- Combines soil nutrient concentrations from Australian Soil Resources Information System (see Appendix 2) with estimates of average annual sediment loads from SedNet modelling (see *Water-borne erosion* section) to estimate the average annual nutrient loads to rivers associated with water erosion.
- Combines estimates of average annual nutrient loads for surface run-off from BIOS modelling (see *Landscape balances* section), with point source data from the National Pollutant Inventory (www.environment.gov.au/epg/npi/database/database.html) to estimate the average annual loads of dissolved nutrient to rivers.

Annual Network Nutrient Export considers the following nutrient source terms at each network link (Figure 6.1):

- sediment-attached nutrients from hillslope erosion (from SedNet);
- sediment-attached nutrients from gully erosion (from SedNet);
- sediment-attached nutrients from river channel bank erosion (from SedNet);
- dissolved nutrients in surface run-off and subsurface drainage (from BIOS/Equil); and
- point source nutrient discharges (from National Pollutant Inventory database).

Nutrients are transported in both dissolved and sediment-attached forms. The model assumes that the:

- sediment-attached nutrient load is associated with the clay fraction of the sediment being transported entirely in suspension; and
- capacity for transport of nutrients both in dissolved forms and associated with suspended sediments is unlimited.

Annual Network Nutrient Export also models the exchange of phosphorus between the suspended sediment and dissolved forms. This process is described by an adsorption coefficient (K_s) that expresses changes in particulate phosphorus concentrations as a ratio of the resulting proportional change in dissolved phosphorus concentrations. K_s is largely determined by sediment particle size and mineralogy. The model assumes that:

- the concentration of phosphorus adsorbed to the suspended sediment is in equilibrium with the dissolved phosphorus concentration;
- the system is in steady-state;
- phosphorus transport associated with phytoplankton is a small component of the total budget; and
- there is no exchange between dissolved and sediment-bound nitrogen.

Loss of dissolved nitrogen by denitrification is modelled as an exponential decay process dependent on the residence time of flow in the network link, water temperature, and a rate constant that varies according to river substrate type

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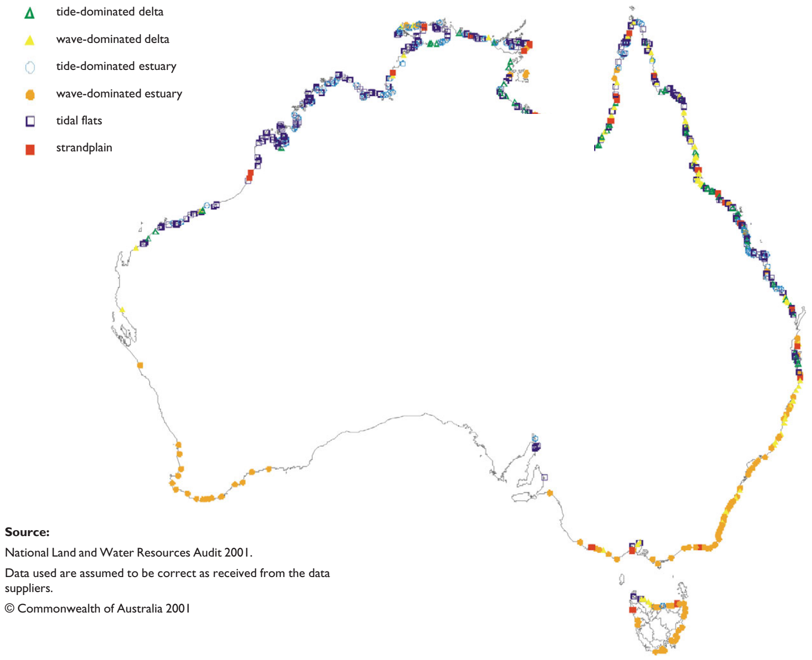
* A link is the stretch of river between tributaries.

Figure 6.2 Australian estuary types.



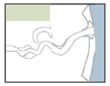
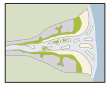
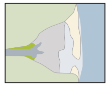
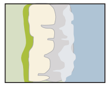
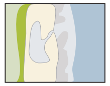
Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

The processes that control movement of nutrients and sediments in Australia's estuaries vary, but can be grouped into six broad categories (Figure 6.2). Tidal-dominated estuaries move suspended sediments and associated bound and dissolved nutrients relatively efficiently from the estuary to the near shore and marine environments. Table 6.1 outlines the major process for deposition and movement to sediments by estuary types.

Table 6.1 Sediment, processes and characteristics in Australian estuary types*.

Type of coastal environment	Sediment trapping efficiency	Turbidity	Circulation	Risk of sedimentation
 Tide-dominated delta	low	naturally high	well mixed	low
 Wave-dominated delta	low	naturally low partially mixed	salt wedge/	low
 Tide-dominated estuary	moderate	naturally high	well mixed	moderate
 Wave-dominated estuary	high	naturally low partially mixed	salt wedge/	high
 Tidal flats	low	naturally high	well mixed	low
 Strandplains	low	naturally low wedge/partially mixed	negative/salt	low

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* Details of the assessment of Australia's estuaries are reported in *Australian Catchment, River and Estuary Assessment 2001* and the Australian Natural Resources Atlas.

Assessment area and scope

The assessment area defined by the Working Group on Land Resource Assessment (as part of the Australian Soil Resources Information System project) includes:

- all river basins that contain areas of intensive land use;
- selected river basins (in the Northern Territory and the western division of the Murray–Darling Basin) that do not contain intensive land use, but for which resource data were available—whole river basins were used so that processes such as hydrology and sediment and nutrient movement could be modelled and balanced over entire river basins.

The Annual Network Nutrient Export model was run for each of the 18 regions (see Figure 5.1, p. 163) used by SedNet to provide prediction of nutrient budget terms link-by-link* for river networks across the assessment area. The model was calibrated using estimates of nutrient loads from field measurements from 93 sites across Australia. Detailed descriptions of the model and the calibration process are provided in a technical report available on the Australian Natural Resources Atlas.

Biological nutrient stores in rivers are ignored by Annual Network Nutrient Export, but predictions of increased nutrient loads indicate the potential for changed biological response:

- increases in nutrient loads can lead to increases in the frequency and size of algal blooms; and
- increases in nutrient loads have been shown to increase the biomass of aquatic plants and higher trophic levels, and to change the composition of aquatic communities often leading to reduced biodiversity (e.g. Schindler et al. 1971, Cole 1973, Edmonson & Lehman 1981, Vollenweider 1992).

Aquatic organisms respond to nutrient *concentrations* rather than to nutrient *loads*. Nutrient concentrations will generally:

- increase with increasing nutrient loads; and
- vary with flow and other aspects of water quality.

Predicting actual ecological response to increased nutrient loads is difficult—a large proportion of the load is moved by floods and may pass through the river network with little ecological impact (e.g. rivers with high efficiency of sediment and nutrient delivery). Reservoirs and estuaries represent nutrient stores, and because all of the nutrients stored in these water bodies can be considered as ultimately bio-available, ecological responses are more closely related to total nutrient loads.

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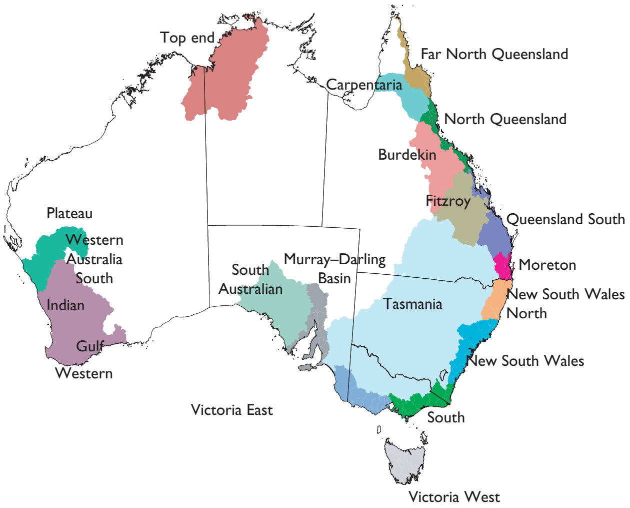
* A link is the stretch of river between tributaries.

Constructing nutrient budgets

Budgets of average annual total nutrient loads were constructed for each major region and for each river basin (Tables 6.2, 6.3, 6.4, 6.5 and Appendix 1); only nutrient budgets were compiled for the connected drainage network for the Murray–Darling Basin region (i.e. those streams and rivers that are connected through the network to the basin outlet). Three river basins (Paroo River, Lake George, Wimmera-Avon Rivers) do not contribute to the basin outlet in this network. Estimates of net exports for river basins include contributions from upstream basins, to cope with the subdivision of the Murray–Darling Basin and the Avon (Western Australia) basin into multiple river basins. In the Murray–Darling it was assumed that:

- the Murray–Riverina receives the outputs of the Upper Murray, Kiewa, Ovens, Broken, Goulburn, Campaspe, Loddon;
- the Murray then flows along the border of Benanee (where the outputs from the Lachlan and Murrumbidgee are added);
- the Darling receives the outputs of the Border Rivers, Moonie, Condamine–Culgoa, Warrego, Gwydir, Namoi, Castlereagh, and Macquarie–Bogan; and
- the Lower Murray receives the outputs from the Darling basin and the Murray River in the Benanee basin, as well as small inputs from the Mallee.

Nutrient budget values for basins along the Murray River are less accurate than statistics for other basins, because the Murray River forms the boundary of some basins. Moreover, while the river is nominally defined to be in New South Wales, the location of the river in the 9 second digital elevation model (used to define the river network for this assessment) falls alternately in adjoining basins, depending on the mapped location of the basin boundary. This puts different sections of the Murray River into each of these adjoining basins.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Table 6.2 Total phosphorus budgets (t/yr) by major region.

Region	Hillslope PP	Gully PP	Bank PP	Point source DP	Run-off DP	Floodplain sedimentation PP	Reservoir sedimentation PP	Export TP	Export percent	Times natural
Far North Qld	2 942	106	144	0	114	1 184	0	2 122	11	2.6
North Qld	3 966	129	187	155	158	1 292	140	3 163	17	2.3
Burdekin	11 909	1 271	309	0	178	8 185	2 960	2 522	13	5.9
Fitzroy	9 526	1 008	519	0	248	8 377	919	2 006	11	7.0
Moreton Bay	971	93	209	597	73	538	254	1 153	6	4.4
Qld South	2 426	336	277	53	164	1 748	362	1 146	6	4.4
Murray–Darling Basin	10 719	4 387	4 434	124	1 306	16 295	3 977	699	4	2.6
NSW North	987	277	396	5	199	572	10	1 282	7	3.6
NSW South	1 902	667	428	101	283	1 314	279	1 788	9	2.8
Vic East	207	183	216	4	266	303	13	559	3	1.5
Vic West	41	213	174	0	144	285	17	269	1	1.9
SA Gulf	146	204	78	9	152	309	19	262	1	2.3
WA South	53	1 009	299	146	569	1 254	17	805	4	2.6
Indian	46	342	111	0	81	466	0	115	1	6.5
Tasmania	244	87	358	137	303	73	25	1 031	5	1.3
Totals/averages	46 086	10 312	8 138	1 331	4 240	42 194	8 992	18 921	100	2.8

TP is total phosphorus, PP is particulate (sediment-bound) phosphorus, DP is dissolved phosphorus. All loads are in tonnes per year (t/yr), and the *export percent* is the region export as a percentage of the assessment area total. *Times natural* is the network link-averaged increase in multiples of the pre-European load.

Table 6.3 Relative (%) magnitude of phosphorus source and sink terms for the major regions and for the assessment area.

Region	% hillslope PP	% gully PP	% bank PP	% point source DP	% run-off DPS	% floodplain PP	% reservoir PP	% export TP
Far North Queensland	89	3	4	0	3	36	0	64
North Queensland	86	3	4	3	3	28	3	69
Burdekin	87	9	2	0	1	60	22	18
Fitzroy	84	9	5	0	2	74	8	18
Moreton Bay	50	5	11	31	4	28	13	59
Queensland South	75	10	9	2	5	54	11	35
Murray–Darling Basin	51	21	21	1	6	78	19	3
New South Wales North	53	15	21	0	11	31	1	69
New South Wales South	56	20	13	3	8	39	8	53
Victoria East	24	21	25	0	30	35	1	64
Victoria West	7	37	30	0	25	50	3	47
South Australia Gulf	25	35	13	2	26	52	3	44
Western Australia South	3	49	14	7	27	60	1	39
Indian	8	59	19	0	14	80	0	20
Tasmania	22	8	32	12	27	6	2	91
Averages	65	15	12	2	6	60	13	27

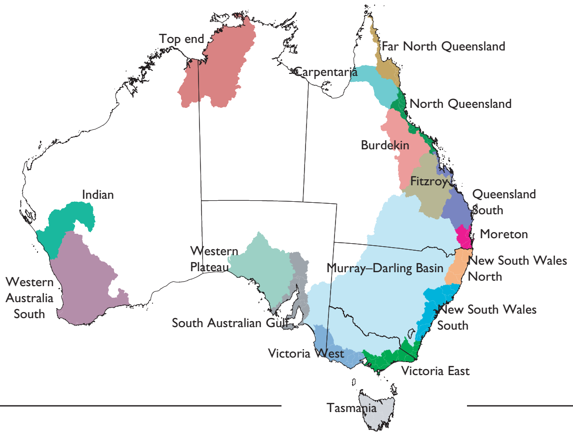


Table 6.4 Nitrogen budgets (t/yr) by major region.

Region	Hillslope PN	Gully PN	Bank PN	Point source DN	Run-off DN	Floodplain sedimentation PN	Reservoir sedimentation PN	Dentrification DN	Export TN	Percent	Times natural
Far North Qld	15 457	425	575	0	2 487	5 826	0	190	12 928	5	1.9
North Qld	15 789	515	746	175	3 486	5 123	559	174	14 854	6	2.2
Burdekin	33 615	5 084	1 234	0	3 915	23 528	7 695	2 359	10 266	12	3.6
Fitzroy	29 108	4 033	2 077	0	5 692	27 086	3 112	1 877	8 834	11	3.3
Moreton Bay	5 205	373	837	1 348	1 616	2 035	1 747	244	5 353	3	2.6
Qld South	9 179	1 346	1 108	49	3 646	6 501	1 290	714	6 822	4	2.4
Murray–Darling Basin	36 352	17 556	17 736	1 208	33 126	53 309	15 952	22 388	14 330	29	2.1
NSW North	7 759	1 108	1 583	0	4 511	3 682	38	427	10 815	4	2.2
NSW South	8 926	2 666	1 710	663	6 442	5 364	1 590	804	12 650	6	1.8
Vic East	1 500	731	865	253	5 897	1 222	39	699	7 285	3	1.3
Vic West	527	851	694	0	3 318	1 167	78	537	3 609	1	1.7
SA Gulf	905	815	313	31	3 975	1 294	65	1 349	3 332	2	2.6
WA South	982	4 038	1 196	694	15 282	4 481	57	5 250	12 404	6	2.5
Indian	445	1 368	444	0	2 032	1 972	0	1 016	1 301	1	2.7
Tasmania	1 536	348	1 432	518	6 774	369	255	170	9 815	3	1.2
Totals/averages	170 264	43 999	34 130	4 938	108 792	148 605	32 559	39 699	141 258	100	2.1

TN is total nitrogen, PN is particulate (sediment-bound) nitrogen, DN is dissolved nitrogen and all loads are in t/yr. *Times natural* is the network link-averaged increase in multiples of the natural load.

Table 6.5 Relative (%) magnitude of nitrogen source and sink terms for the major regions and for the assessment area.

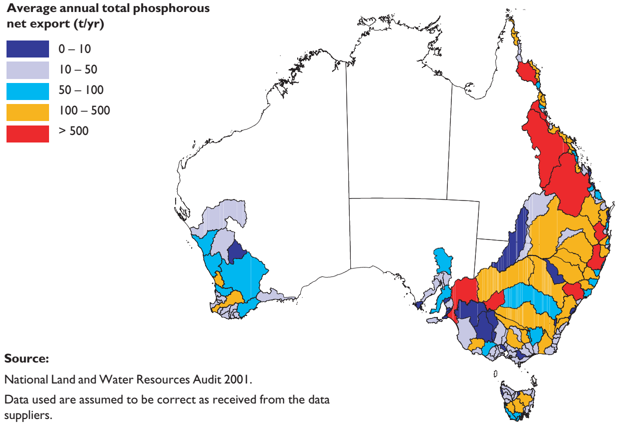
Region	% hillslope PN	% gully PN	% bank PN	% point source DN	% run-off DN	% floodplain sedimentation PN	% reservoir sedimentation PN	% dentrification DN	% export TN
Far North Qld	82	2	3	0	13	31	0	1	68
North Qld	76	2	4	1	17	25	3	1	72
Burdekin	77	12	3	0	9	54	18	5	23
Fitzroy	71	10	5	0	14	66	8	5	22
Moreton Bay	55	4	9	14	17	22	19	3	57
Qld South	60	9	7	0	24	42	8	5	45
Murray–Darling Basin	34	17	17	1	31	50	15	21	14
NSW North	52	7	11	0	30	25	0	3	72
NSW South	44	13	8	3	32	26	8	4	62
Vic East	16	8	9	3	64	13	0	8	79
Vic West	10	16	13	0	62	22	1	10	67
SA Gulf	15	13	5	1	66	21	1	22	55
WA South	4	18	5	3	69	20	0	24	56
Indian	10	32	10	0	47	46	0	24	30
Tasmania	14	3	14	5	64	3	2	2	93
Totals/Averages	47	12	9	1	30	41	9	11	39

Total exports

A strong contrast exists between patterns of phosphorus and nitrogen export. This is mainly due to the greater proportion of the total nitrogen load being transported in dissolved form. The low sediment delivery ratio dominating total phosphorus delivery for the Murray–Darling is a lesser influence on total nitrogen delivery.

- On average, it is estimated that from the rivers assessed, nearly 19 000 tonnes of total phosphorus are currently exported to the Australian coast each year: the largest export is from North Queensland, and over half the total exported comes from just four regions: North Queensland, Far North Queensland, the Burdekin, and the Fitzroy. This represents an average of nearly 10 000 tonnes of phosphorus delivered to the Queensland estuaries and coast each year.
- The average total nitrogen export is estimated to be around 141 000 tonnes per year, with the largest export being from the Murray–Darling.
- Five river basins are predicted to be net sinks for phosphorus: Murray–Riverina, Benanee, Castlereagh*, Darling and Lower Murray.
- At the basin level, the Burdekin, followed by the Fitzroy, are the largest exporters of phosphorus because although their export rates are not excessive, they are both large basins. The pattern of phosphorus net exports by river basin (Figure 6.3) shows the predominance of these two basins, but also highlights large exports from the Normanby, Herbert, and Brisbane rivers in Queensland and the Clarence and Hunter rivers New South Wales, as well as the large Murray–Darling Basin.
- The pattern of nitrogen net exports from basins (Figure 6.4) shows large exports from the big Murray–Darling, Burdekin and Fitzroy basins. Substantial nitrogen loads are exported from several of the river basins within the Murray–Darling, in particular the Murray and Murrumbidgee rivers.

Figure 6.3 Average net total phosphorus export by Australian Water Resources Council basin.

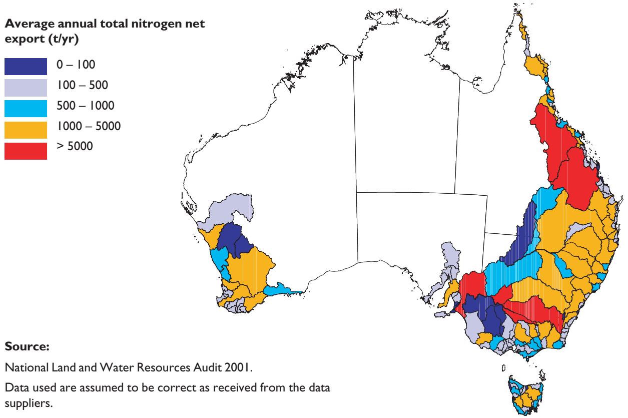


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 6.4 Average net total nitrogen export by river network.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

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* The Castlereagh result is spurious, and is caused by the length of the Darling River that flows along its border in which significant deposition occurs. This is a result of the river and basin mapping, as outlined for the Murray River.

Relative sizes of sources and sinks

Phosphorus sources

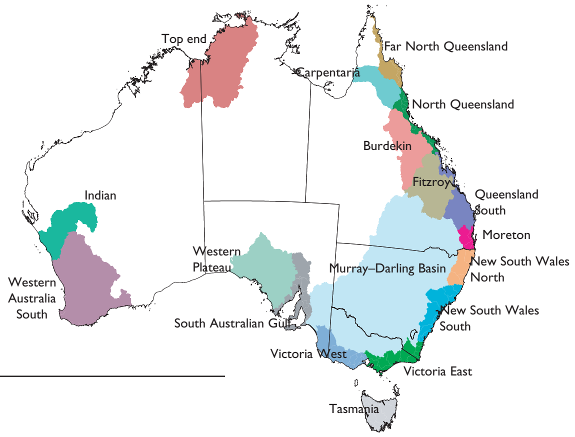
- Most phosphorus comes from hillslope erosion (65%) with loads as high as 85% in those regions contributing the largest loads.
- Gully erosion contributes a high proportion of total phosphorus load in some regions (e.g. gully erosion represents 59% of the load in the Indian Ocean region).
- Urban point source discharges represent 31% of the total phosphorus load in the Moreton Bay region. A large proportion of this enters the lower Brisbane River and can be expected to have significant ecological consequences for the lower river and Moreton Bay.

Phosphorus sinks

- 60% of the phosphorus load that reaches river networks is deposited on floodplains with fine sediment.
- 27% of the phosphorus load that reaches river networks is exported to the coast.
- 13% of the phosphorus load that reaches river networks is deposited in reservoirs with fine sediment. This particulate phosphorus should be considered in the long term as being bio-available for phytoplankton growth. The largest load of particulate phosphorus deposited in reservoirs occurs in the Murray–Darling, a region with a large number of reservoirs and a recent history of reservoir cyanobacteria bloom problems.

The efficiency of phosphorus delivery varies greatly between the regions.

- Small coastal catchments in Tasmania export over 90% of the phosphorus that reaches the drainage network.
- In the Murray–Darling only 3% of phosphorus is exported, but this applies only to the connected drainage network. This delivery ratio would be lower, if large areas of unconnected drainage had been assessed.



Nitrogen sources

The sources of sediment for particulate nitrogen were assumed to be the same as those for particulate phosphorus.

- Most nitrogen comes from hillslope erosion (65%) with loads as high as 85% in those regions contributing the largest loads.
- Gully erosion contributes a high proportion of total nitrogen load in some regions.

Dissolved nitrogen contributes a greater proportion of the total nitrogen source than does dissolved phosphorus of the total phosphorus source.

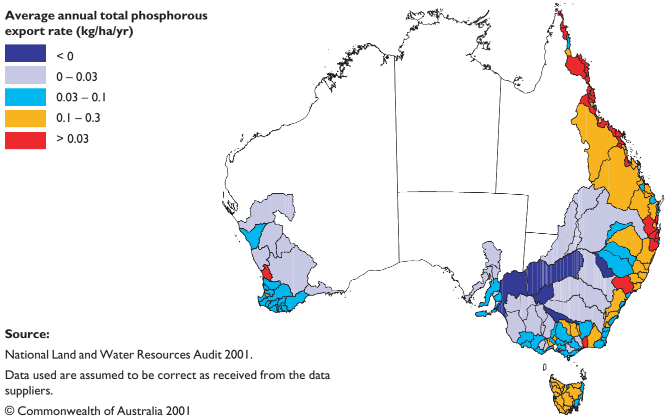
- On average, from 30% to 69% of total nitrogen load exists as dissolved nitrogen in the Western Australia's southern region.

Nitrogen sinks

Information on the sinks for nitrogen provides valuable guidance for land and stream management. With less of the total nitrogen load transported in particulate forms, the percentage losses to floodplain and reservoir sedimentation are lower.

- Overall, export is 39% on average because of extra losses (11% on average) of nitrogen from the river system through denitrification. The percentage denitrification losses vary between regions from as high as 22% in Western Australia South and Indian Ocean regions, to as low as 1% in North and Far North Queensland. Denitrification losses are highest where the water residence times are longest in the lower gradient rivers with extended periods of low or very low flows.
- Percentage exports range from 93% in Tasmania where the dissolved nitrogen fraction is high and denitrification losses are low (down to 14% in the Murray–Darling where both sedimentation and denitrification losses are high).

Figure 6.5 Average annual total phosphorus export rate by Australian Water Resources Council basin.

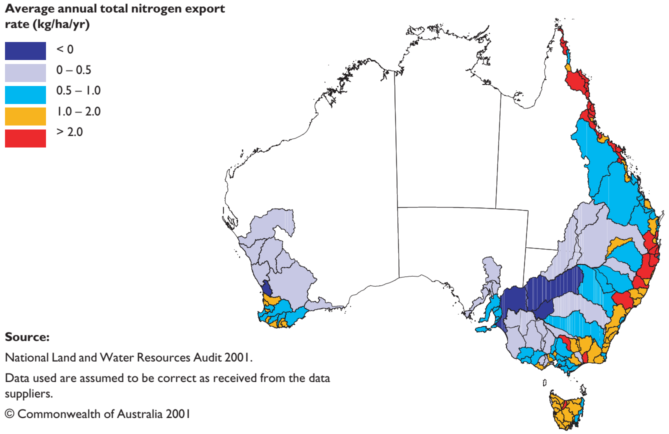


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 6.6 Average annual total nitrogen export rate by Australian Water Resources Council basin.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Area-based nutrient export rates

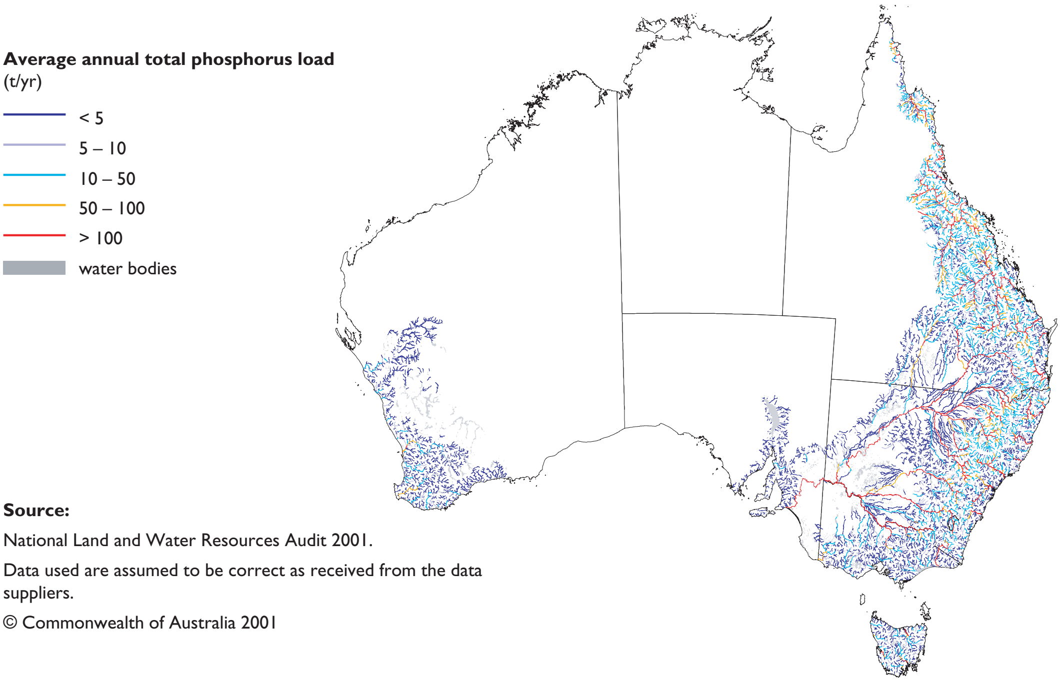
Mapping total nutrient loads across drainage network links (Figures 6.5, 6.6) shows that the largest rivers generally carry the largest nutrient loads. Dividing these loads by the upstream catchment or basin area provides *area-based nutrient export* rates. Export rates indicate the differences in nutrient source intensity from:

- natural differences in topography and rainfall that give rise to natural differences in erosion rates; and
- differences due to intensity of resource use—more intensive resource use increases export rates by increasing soil erosion, loss of fertiliser nutrients, run-off of animal wastes and point source discharges.

The highest export rates are generally a result of high erosion rates driven by topography, rainfall and land use.

- Averaged across river basins, the total phosphorus export rate was predicted to be 0.11 kg/ha/yr and the total nitrogen export rate was estimated at 0.85 kg/ha/yr.
- Export rates ranged from zero to as high as of 2.4 kg/ha/yr for total phosphorus and to 10.5 kg/ha/yr for total nitrogen from the Mulgrave–Russell rivers in Far North Queensland (Figures 6.4, 6.5).

Figure 6.7 Average annual total phosphorus export by river network.

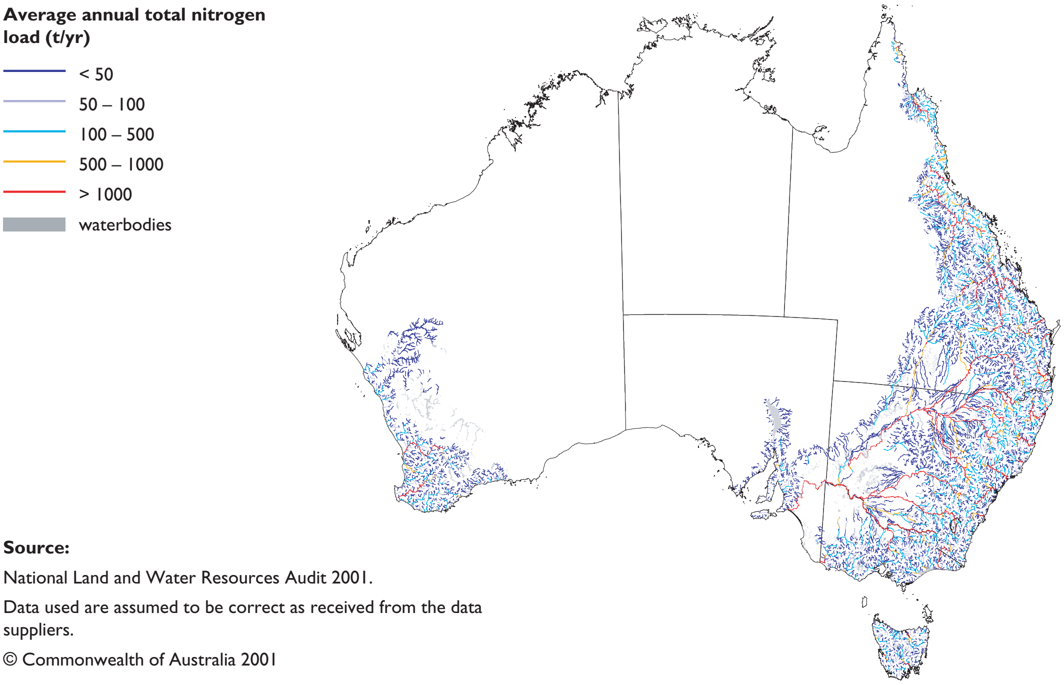


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 6.8 Average annual total nitrogen export by river network.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Changes in total nutrient loads

Increases in nutrient load

Across the assessed basins, the average total annual phosphorus load increased 2.8 times relative to pre-European levels.

- At the region scale, the river link-averaged increases ranged from a seven times increase in the Fitzroy basin to a 30% increase in Tasmania (Table 6.2).
- At the river basin scale (Appendix 1, Figure 6.9), total phosphorus loads have increased by more than 10 times in the river networks of the Proserpine, O'Connell and Styx basins in Queensland, all of which drain to the Great Barrier Reef lagoon.

Significant increases in total phosphorus of between 5 and 10 times have occurred in the rivers of the large Burdekin, Fitzroy, Burnett, and Brisbane basins in Queensland; nine other smaller basins along the Queensland coast; the Border Rivers, Gwydir and Namoi basins in upper Murray–Darling Basin; and the Greenough and Murchison basins in Western Australia.

Figure 6.9 Relative increase in average annual total phosphorus loads by Australian Water Resources Council basin.

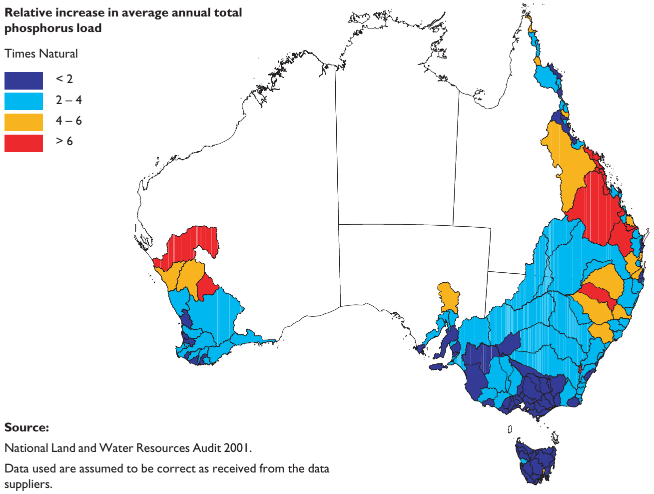


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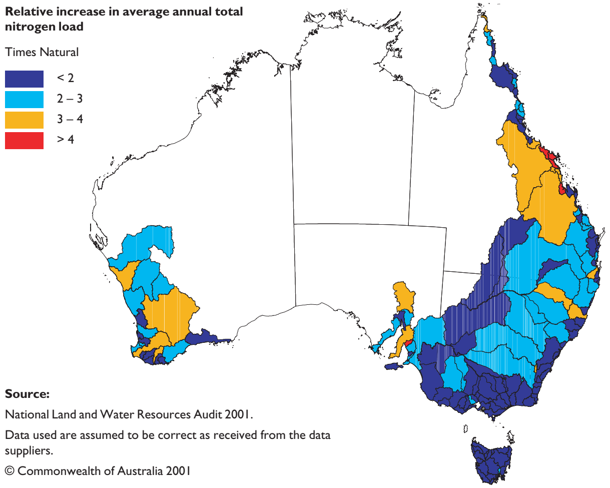
Figure 6.10 Relative increase in average annual total nitrogen loads by Australian Water Resources Council basin.



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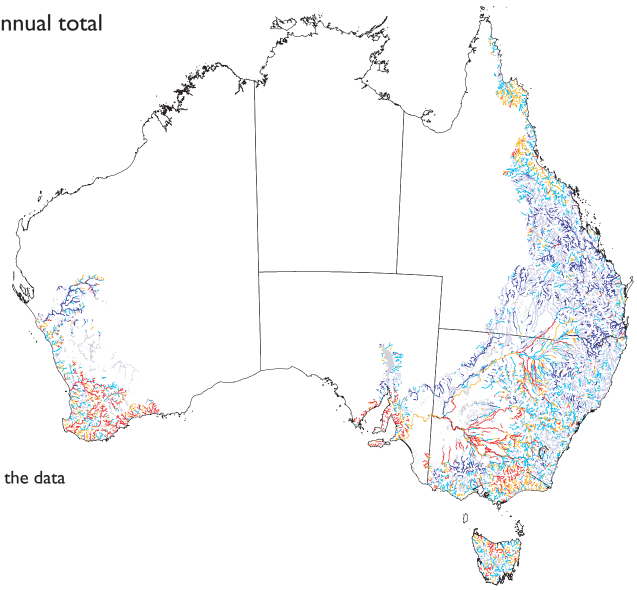
Across the assessed basins the average total annual nitrogen loads increased 2.1 times.

- At the region scale, the river link-averaged increase ranges from a 3.6 times increase in the Burdekin to a 20% increase in Tasmania (Table 6.4).
- At the river basin scale (Appendix 1, Figure 6.10), total nitrogen loads have increased by more than 4 times in the river networks of the Don, O'Connell, Styx and Proserpine basins in Queensland; and in the Wakefield basin in South Australia.
- Significant increases in total nitrogen loads of between 3 and 4 times have occurred in the rivers of the large Burdekin, Fitzroy, Burnett, and Brisbane basins in Queensland; five other smaller basins along the Queensland coast; the Gwydir and Namoi basins in upper Murray–Darling Basin; the Macleay River in coastal New South Wales; the Broughton and Lake Torrens basins in South Australia; and the Murchison, Blackwood, Frankland and Avon basins in Western Australia.

Spatial patterns

Basin averages must be interpreted with care, since increases in nutrient loads are not evenly distributed (Figures 6.11, 6.12). For example, several basins in the New South Wales section of Murray–Darling Basin showed much larger increases in total phosphorus in the upper reaches compared to the lower reaches, because of intense gully erosion along the western slopes of the Great Dividing Range.

Figure 6.11 Relative increase in average annual total phosphorus loads by river network.

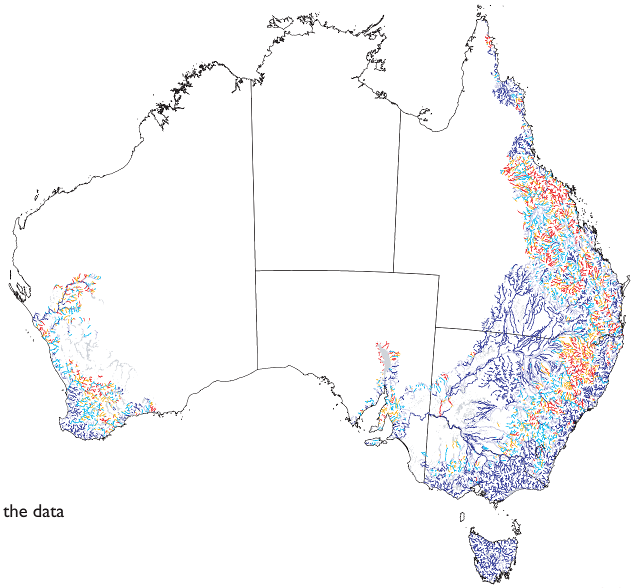


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 6.12 Relative increase in average annual total nitrogen load by river network.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Where nutrient loads have increased by over 3.5 times, it is likely that aspects of the rivers will be substantially degraded:

- In many basins (particularly in Queensland and Western Australia) over 75% of the stream length has been degraded by increases in total phosphorus loads (Figure 6.13).
- In a few basins (including the Avon, the Gwydir, the Broughton, the Wakefield and several coastal Queensland basins) over 75% of the stream length has been degraded by increases in total nitrogen loads (Figure 6.14).

Figure 6.13 Percentage of stream length that is degraded by increased average annual total phosphorus loads by Australian Water Resources Council basin.

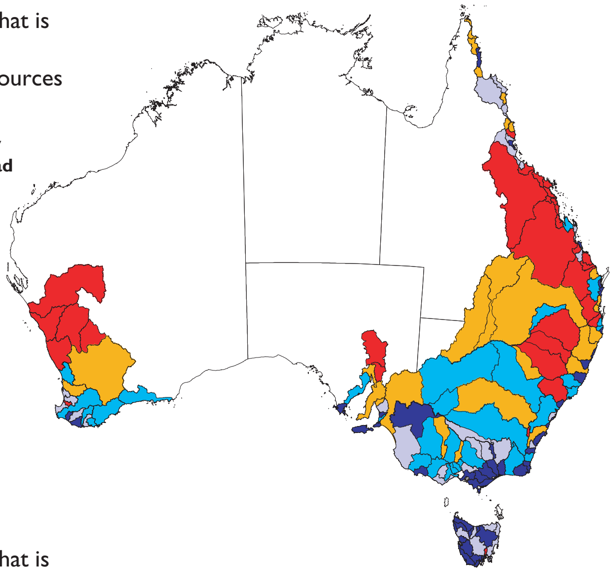
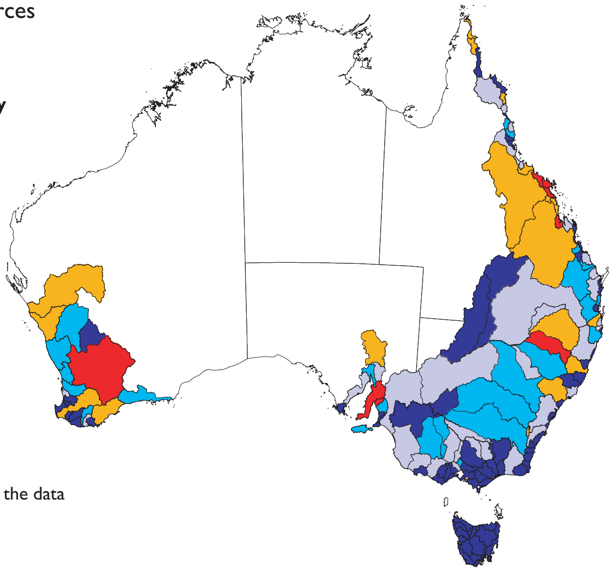


Figure 6.14 Percentage of stream length that is degraded by increased average annual total nitrogen loads by Australian Water Resources Council basin.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Not all basins with large increases in river nutrient loading also *export* large loads. Comparison of river link-averaged values indicates potential impacts on river condition, but does not necessarily translate to equivalent increases in basin export (e.g. the Paroo basin shows a moderate increase in link-averaged phosphorus loading, but does not export phosphorus under the natural or the currently modelled scenario).

Nutrient exports need to be linked back to catchment land uses, because nutrient loss pathways for dissolved and sediment-bound nutrients differ and may require different control practices.

Phosphorus

In the case of phosphorus, exchanges between dissolved (in water) and sediment-bound phosphorus pools occur during transport. The percentage increase in the load that is caused by each of four major source types has been determined (Appendix 1).

- phosphorus load increases are dominated by increases in channel (gully and stream bank) erosion in 61% of basins (or 45% by basin area); by increases in hillslope erosion in 36% of basins (or 55% by basin area), and by point sources in just four basins (Maroochy, the Queensland South Coast, the Onkaparinga and the Swan Coast—less than 1% by basin area).

Nitrogen

- Nitrogen load increases are dominated by increases in channel erosion in 40% of basins (or 39% by basin area); by increases in hillslope erosion in 40% of basins (or 49% by basin area); by increases in surface run-off loads in 17% of basins (or 10% by basin area); and by point sources in four basins (Queensland South Coast, the Maribyrnong, the Onkaparinga and the Swan Coast—less than 1% by basin area).
- Nitrogen load increases in several basins are dominated by dissolved nitrogen in surface run-off. These increases reflect both increased nutrient inputs via fertiliser and dissolved organic losses associated with changes in vegetation type. Particular care with fertiliser management is required in those regions where increases in dissolved nutrient loads are a high percentage of the total increase.

NUTRIENT FORMS AND LIKELY ECOLOGICAL IMPACTS

Nutrient forms

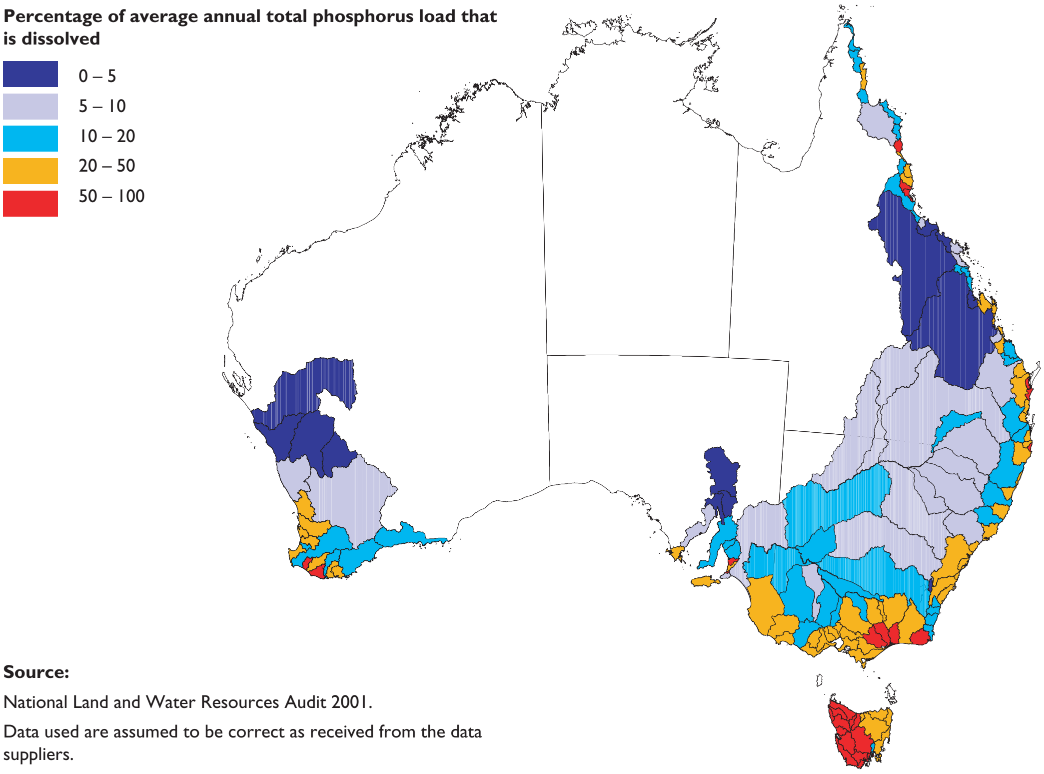
Phosphorus

Particulate phosphorus occurs in organic and inorganic forms (inorganic particulate phosphorus mainly occurs as phosphate ions chemically adsorbed to eroded clay mineral particles)

Dissolved phosphorus is immediately available to aquatic plants and algae, but particulate phosphorus can change into the dissolved form as local water quality conditions change.

Most or all of the phosphorus in transport has the potential to be bio-available in the long term. In the short term, the ability of the suspended sediment in a river to provide phosphorus for algal growth beyond that in the dissolved fraction is described by the relative buffering capacity (Froelich 1988), which is proportional to the inverse of the ratio of dissolved phosphorus to total phosphorus. That is, for low values of this ratio the buffering capacity is high, and for high values of this ratio the buffering capacity is low.

Figure 6.15 Percentage of average annual total phosphorus load dissolved by Australian Water Resources Council basin.

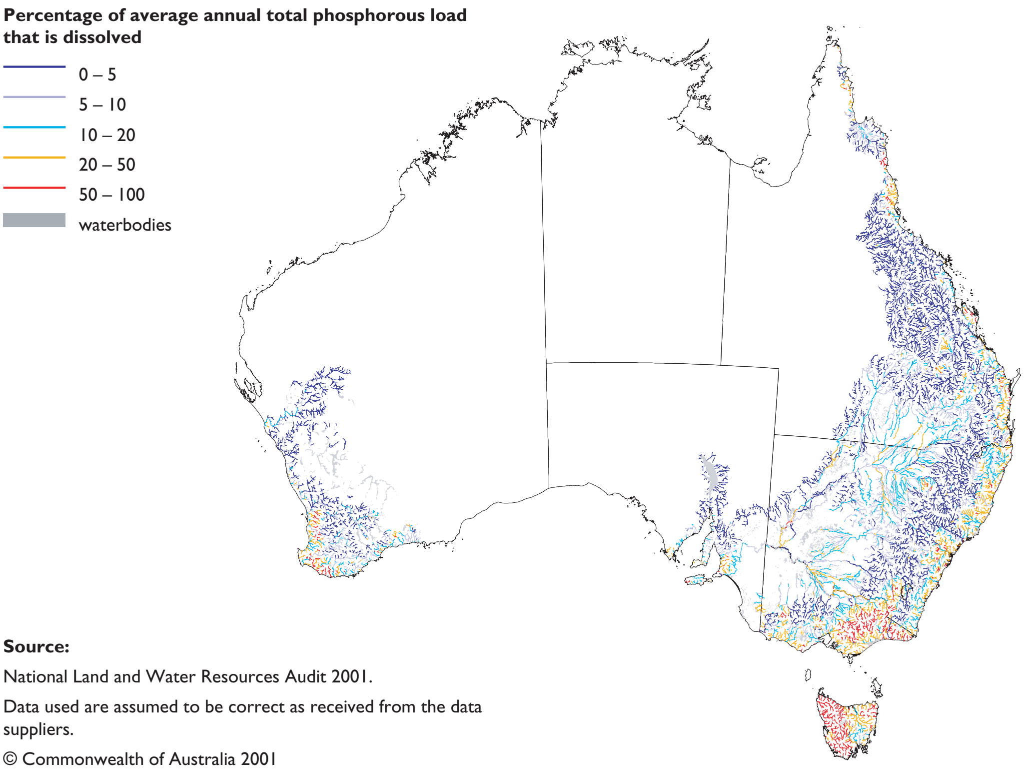


Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

Figure 6.16 Percentage of average annual total phosphorus load that is dissolved by river network.



Source:

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Data used are assumed to be correct as received from the data suppliers.

Variation in the ratio of dissolved to total phosphorus (Figures 6.15, 6.16) shows a spatial pattern in relative buffering capacity, and hence differences between rivers in their short-term ability to provide phosphorus from suspended sediments for algal growth.

- At the river basin scale, this ratio ranges from 0.01 in the Lake Torrens basin in South Australia to 0.97 in the Pieman River basin in Tasmania; with a basin average of 0.28. Generally, the highest values are for the rivers of Tasmania, east Victoria and parts of the south west of Western Australia. The low values for the major inland basins and the rivers of the Indian Ocean region, indicate the high relative buffering capacity of these rivers. In these basins, suspended sediments can be expected to act as a reasonably available source of phosphorus for algal growth should dissolved phosphorus become depleted.

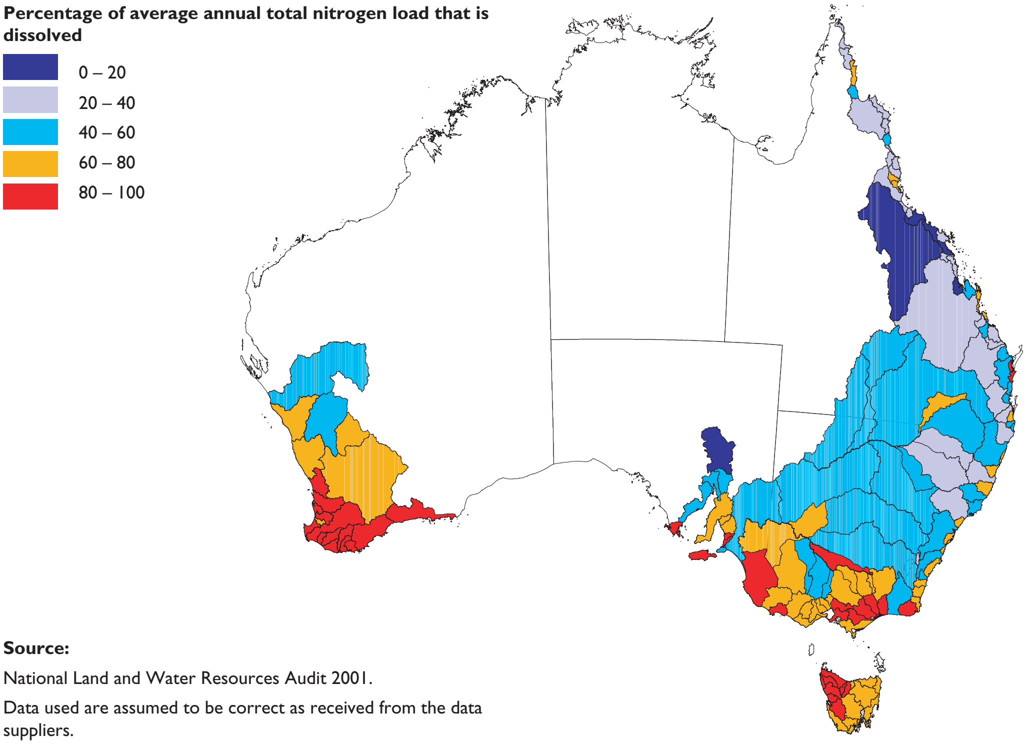
Nitrogen

Most of the particulate nitrogen is organic, although some exists as ammonium chemically bound to sediments.

Dissolved nitrogen is more available to most aquatic plants and algae than other forms, although ammonium is relatively easily stripped from sediments for biological uptake. However, ammonium is only a small fraction of total load and the ratio of the dissolved load to the total nitrogen load is a reasonable indicator of the proportion of the nitrogen load that is readily available to aquatic plants and algae (Figures 6.17, 6.18).

- At the river basin scale, the nitrogen ratio ranges from 0.08 in the Don River in Queensland to 0.98 in the Shannon River in the south-west of Western Australia. The Australian basin average was 0.61. Generally, the highest values are for the rivers of south-west Western Australia, north-west Tasmania and parts of Victoria. In these basins, a high proportion of the total nitrogen load will be readily available for algal growth.

Figure 6.17 Percentage of average annual total nitrogen loads that is dissolved by Australian Water Resources Council basin.



Source:

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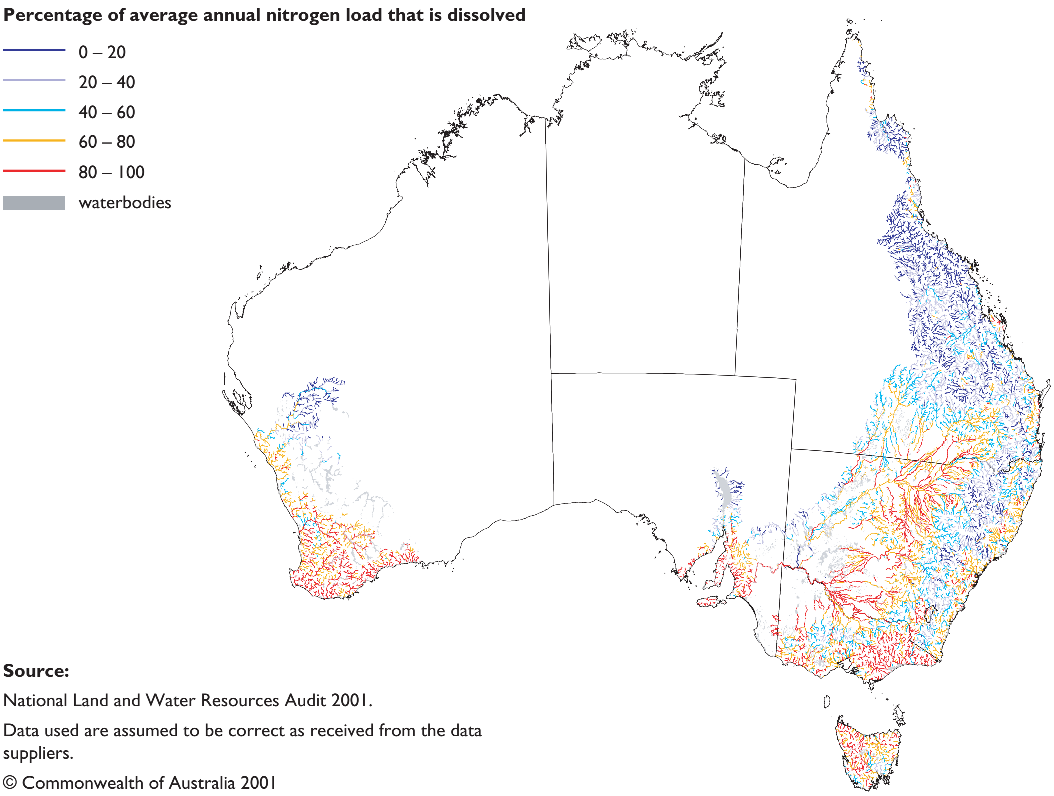
Data used are assumed to be correct as received from the data suppliers.

Figure 6.18 Percentage of average annual total nitrogen loads that is dissolved by river network.



Source:

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Data used are assumed to be correct as received from the data suppliers.

Nitrogen:phosphorus ratios

The ratio of nitrogen to phosphorus in water indicates their relative availability to aquatic organisms. This ratio in algae approximates to the relative amounts of these two nutrients actually used by the algae.

An expression of the nitrogen to phosphorus ratio is known as the 'Redfield ratio' (Redfield 1958). The 'Redfield ratio' defines a threshold value (approximately 6.8, by weight) which can be used to evaluate the nutrient status of a water body.

Total nitrogen to total phosphorus ratios vary for pre-European conditions from slightly less than 6.8 to nearly 20 (Table 6.6). Where turbidity is not extreme and these ratios are high (e.g. south-west of Western Australia) growth of phytoplankton is likely to be phosphorus limited.

Redfield ratio

When the Redfield ratio is greater than 6.8 the water body is regarded as phosphorus deficient, and when it is less than 6.8 it is regarded as nitrogen deficient. Nitrogen deficient conditions favour those species of algae (including many blue-green algal species) that fix atmospheric nitrogen.

The Redfield ratio must be interpreted with caution because of the differing bio-availability of different nutrient forms under different river conditions. They are only a strong determinant of phytoplankton community structure in situations where population growth is primarily limited by nutrient supply. The ratio is less relevant in very turbid rivers, where phytoplankton growth is mainly limited by light.

Table 6.6 Total nitrogen to total phosphorus ratios for the current and natural modelled scenarios, and the ratio of total nitrogen to total phosphorus between current and natural for the major modelling regions.

Region	Current TN/TP	Natural TN/TP	Current/natural TN/TP
Far North Queensland	6.3	8.8	0.77
North Queensland	5.9	9.1	0.70
Burdekin	3.5	6.5	0.59
Fitzroy	4.6	10.3	0.46
Moreton Bay	7.6	15.7	0.49
Queensland South	6.9	14.4	0.49
Murray–Darling Basin	13.2	18.8	0.72
New South Wales North	9.9	17.6	0.57
New South Wales South	10.0	16.3	0.61
Victoria East	16.4	19.8	0.82
Victoria West	17.2	21.0	0.84
South Australia Gulf	21.5	18.2	1.23
Western Australia South	24.7	22.4	1.11
Indian	8.7	21.7	0.52
Tasmania	12.8	15.9	0.86

- Averaged across the entire river network, the pre-disturbance total nitrogen to total phosphorus ratio was close to 17, and is now currently 12.5. This reduction is generally caused by increased sediment loads, that in relative terms, increase total phosphorus loads more than total nitrogen.
- The ratio has increased in some areas (e.g. in parts of south Western Australia, South Australia, Victoria, Tasmania and the lowland rivers of the Murray–Darling Basin [Figures 6.19, 6.20]). However, in these areas the ratios were naturally high, and the change is unlikely to be ecologically important.

Figure 6.19 Relative change in the ratio of average annual total nitrogen load to average annual total phosphorus load by Australian Water Resources Council basin.

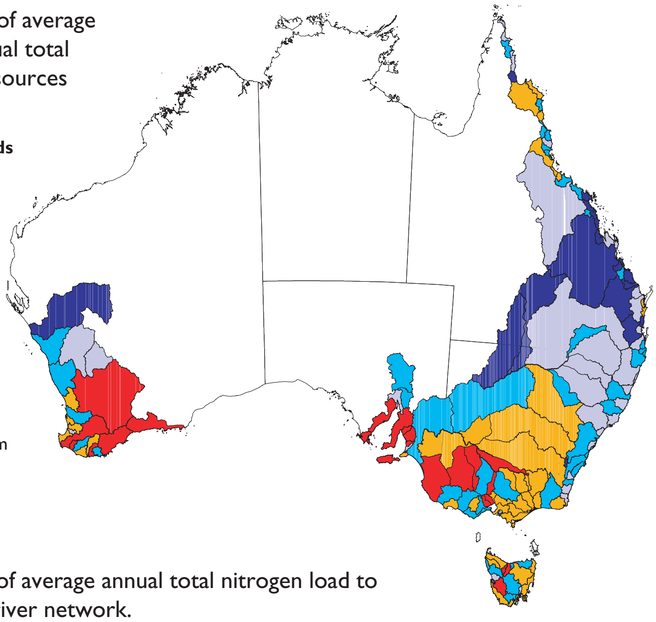

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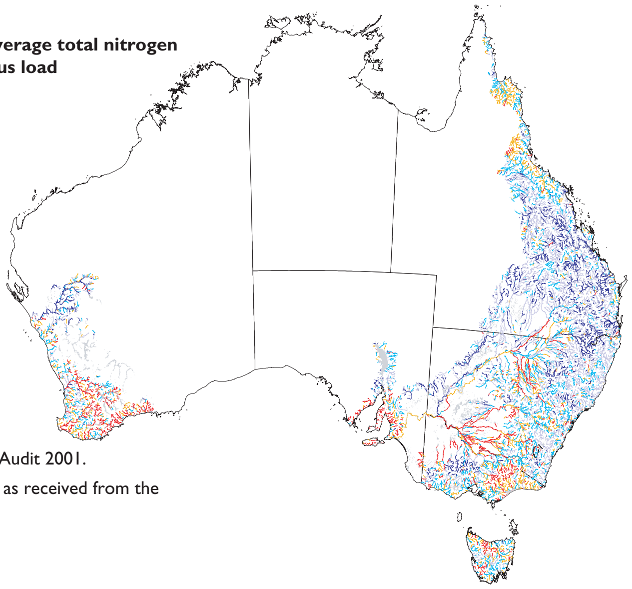
Figure 6.20 Relative change in the ratio of average annual total nitrogen load to average annual total phosphorus load by river network.



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IMPLICATIONS FOR LAND AND WATER MANAGEMENT

- Priority areas for reducing river and estuarine nutrient loads are likely to differ. Large relative increases in river nutrient loads do not always coincide with large total exports, and estuaries differ in their sensitivity to increases in nutrient loading, particularly because of differences in residence times and tidal flushing.
- Erosion control and management will provide a significant benefit to managing supply of nutrients from increased sediment loads to most rivers.
- In areas where a large part of the increase is caused by surface run-off loads or point source discharges, close attention needs to be given to fertiliser applications, ensuring appropriate amounts are applied at appropriate times, and with application methods that minimise run-off losses.
- Point sources from intensive rural industries may be dominant nutrient sources in some catchments. They deserve close attention to ensure adequate retention of nutrients occur on-site.
- The dominant impact of storm events in determining total nutrient loads may mask spatial patterns in the changes in nutrient concentrations at low flows. This is important in determining ecological responses (e.g. the substantial increases in nutrient loads that are predicted to have occurred in some Far North Queensland basins do not match local knowledge of their ecological impact). Further work is required to improve the modelling of regional-scale water quality changes in rivers and land use mapping to include intensity and practice attributes.
- As a consequence of long residence times of fine sediment stores in parts of river systems, the long-term availability of nutrients to river ecosystems has increased in many areas. Dealing with nutrient sources is necessary, but management of these riverine nutrient stores is also required in the future, if adverse ecological responses are to be minimised.

REFERENCES

Brune G.M. 1953, 'Trap efficiency of reservoirs', *Transactions, American Geophysical Union* vol. 34, pp. 407–418.

Cole R.A. 1973, 'Stream community response to nutrient enrichment', *Journal of Water Pollution Control Federation* vol. 45, pp. 1875–1888.

Edmonson W.T. & Lehman J.R. 1981, 'The effect of changes in nutrient income on the conditions of Lake Washington', *Limnology and Oceanography* vol. 26, pp. 1–28.

Froelich P.N. 1988, 'Kinetic control of dissolved phosphate in natural rivers: a primer on the phosphate buffer mechanism', *Limnology and Oceanography* vol. 33, pp. 649–668.

Prosser I.P., Hughes A.O., Rustomji P., Young W. & Moran C.J. 2001, *Assessment of River Sediment Budgets for the National Land and Water Resources Audit*, CSIRO Land and Water Technical Report xx/01 (in press), Canberra.

Redfield A.C. 1958, 'The biological control of chemical factors in the environment', *American Scientist* vol. 46, pp. 205–222.

Schindler D.W., Armstrong F.A.J., Holmgren S.K. & Brunskill G.J. 1971, 'Eutrophication of Lake 227, Experimental Lakes area, Northwest Ontario, by addition of phosphorus and nitrate', *Journal of the Fisheries Research Board Canada* vol. 28, pp. 1763–1782.

Vollenweider R.A. 1992, 'Coastal marine eutrophication: principles and control', in R.A. Vollenweider, R. Marchetti & R. Viniani (eds), *Marine Coastal Eutrophication*, Science of the Total Environment Supplement, Elsevier, Amsterdam.

APPENDIX 1. RIVER BASIN BUDGETS

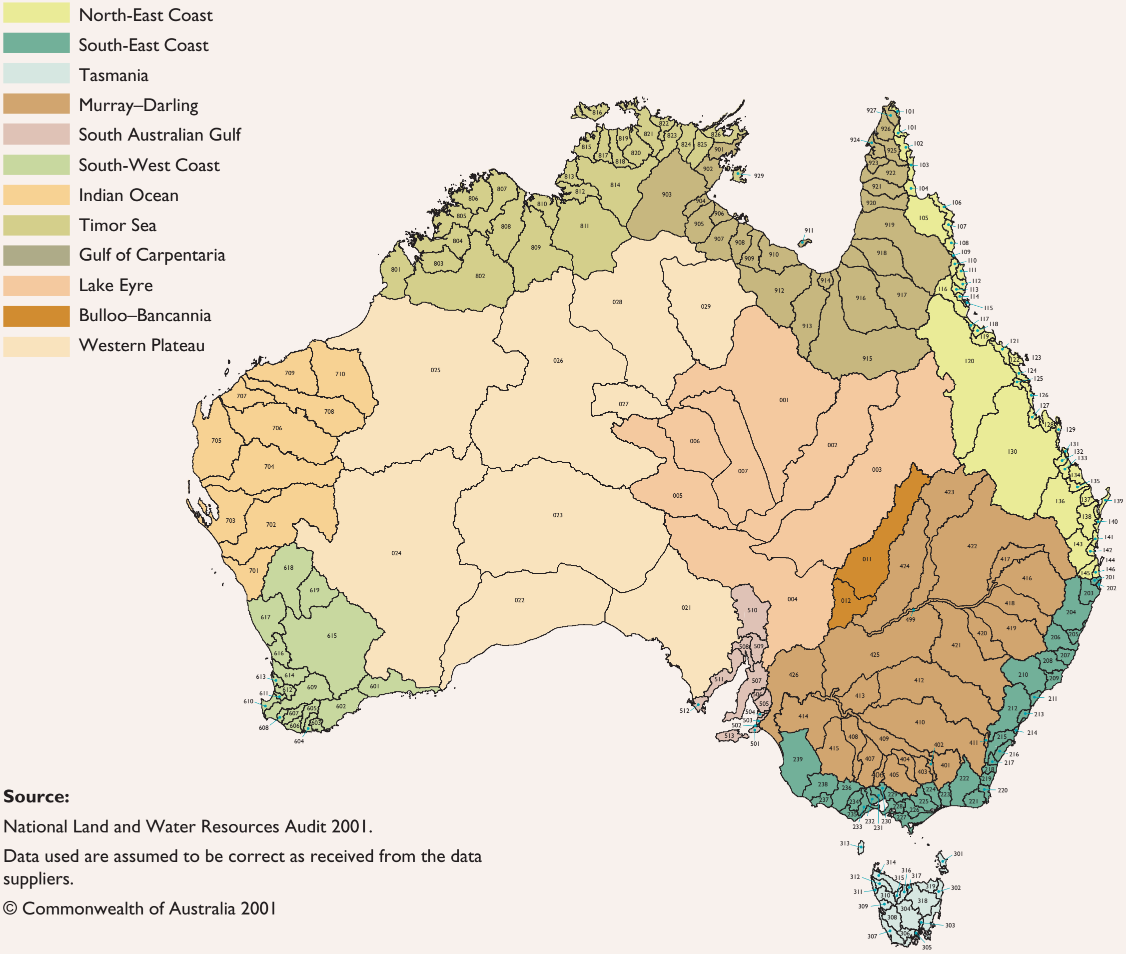
River basin budget terms

Key material budget terms were modelled or collated as part of the Australian Agriculture Assessment 2001 projects. They cover:

- coupled balances of carbon, water, nitrogen and phosphorus;
- water-borne erosion and sediment transport;
- farm-gate nutrient balance; and
- river nutrient transport.

Key river basin characteristics such as brad agricultural land use categories and climate are provided for context. All attributes are presented as aggregate mass, rate, ratio or percentage estimate at a river basin scale (Figure A1).

Figure A1 Australian river basins.



Source:

National Land and Water Resources Audit 2001.

Data used are assumed to be correct as received from the data suppliers.

River basin budget attributes

Attribute	Units	Description
Context		
Basin number	Id	Unique identifier for the river basin
Basin name	Name	River basin name
Basin area	km^2	River basin area
Improved pasture	%	Proportion of basin in Australian Land Use and Management Classification code 12 'Grazing Improved Pastures' (National land use map)
Cropping	%	Proportion of basin in Australian Land Use and Management Classification code 15 'Permanent Cropping' (National land use map)
Horticulture	%	Proportion of basin in Australian Land Use and Management Classification code 10 'Agricultural Land' and Australian Land Use and Management Classification code 14 'Horticulture' (National land use map)
Total agricultural land proportion		Total agricultural land proportion
Climate		
Rain	mm/yr	Mean daily rainfall
Total evaporation	mm/yr	Mean daily total (canopy + soil) evaporation
Run-off	mm/yr	Mean run-off (rain – evaporation)
Carbon and productivity		
Net primary production	t C/ha/yr	Mean net primary productivity (carbon yield, available for human/animal use)
Plant carbon	ha/ha	Plant (biomass) carbon—store of carbon in standing plants
Litter+soil carbon	ha/ha	Litter + soil organic carbon
Landscape nutrients		
Nitrogen from fertiliser	kg N/ha/yr	Nitrogen input flux from fertilisation (disaggregated from statistical local area totals, distributed proportionally by land use)
Nitrogen fixation	kg N/ha/yr	Nitrogen input flux from legumes (disaggregated from statistical local area totals, distributed proportionally by land use)
Total nitrogen	kg N/ha	Total nitrogen (organic litter + organic soil + mineral)
Mineral nitrogen	ha/ha	Mineral nitrogen
Mineral nitrogen concentration in soil water	mg N/kg water	Mineral nitrogen concentration in the soil water

River basin budget attributes

Attribute	Units	Description
Nitrogen leached	kg N/ha/yr	Nitrogen loss flux from leaching
Nitrogen volatilised	kg N/ha/yr	Nitrogen loss flux from volatilisation
Phosphorus from fertiliser	kg P/ha/yr	Phosphorus input flux from fertilisation (disaggregated from statistical local area totals, distributed proportionally by land use)
Total phosphorus	kg P/ha	Total phosphorus (organic litter + organic soil + mineral)
Dissolved mineral phosphorus	kg P/ha	Dissolved mineral phosphorus readily available to plants
Phosphorus concentration	mg P/kg water	Dissolved mineral phosphorus concentration in the soil water
Phosphorus leached	kg P/m^2/yr	Phosphorus loss flux from leaching
Water borne erosion and sediment transport		
Sediment supplied to rivers	t/yr	Total sediment supplied to streams on an annual basis from hillslope erosion, bank erosion and gully erosion. For some river basins the area assessed is less than the total basin area.
Sediment supply	t/ha/yr	Average annual rate of sediment supplied to streams from hillslope erosion, bank erosion and gully erosion.
Hillslope erosion	%	Sum of hillslope erosion (t/yr) divided by the totalsediment supply value for each basin (t/yr)
Streambank erosion	%	Sum of bank erosion (t/yr) divided by the total sediment supply value for each basin (t/yr)
Gully erosion	%	Sum of gully erosion (t/yr) divided by the total sediment supply value for each basin (t/yr)
Length with riverbed deposition	proportion	Stream length in each basin with deposition greater than 0.30 m divided by the total stream length
European to pre- European sediment	Ratio	Average ratio of sediment supply under present land use conditions to that under natural conditions
Sediment export to coast	t/yr	Sediment export to the coast
Contribution of sediment to coast	t/ha/yr	Specific sediment export to the coast
Sediment delivery	Ratio	River sediment delivery ratio (export/supply to streams)
Nutrients delivered to rivers, floodplains, reservoirs and estuaries		
Phosphorus from fine sediments	%	Percentage of average annual total phosphorus load that is delivered to the river network in the basin in association with fine sediment.
Phosphorus from point sources	%	Percentage of average annual total phosphorus load that is delivered to the river network in the basin in dissolved forms from urban sewage and industrial discharges.

River basin budget attributes

Attribute	Units	Description
Phosphorus – dissolved from diffuse sources	%	Percentage of average annual total phosphorus load that is delivered to the river network in the basin in dissolved forms by surface and subsurface run-off.
Phosphorus deposited on floodplain	%	Percentage of average annual total phosphorus load basin that is deposited with fine sediment on river floodplains in the basin. For internal basins this figure includes the contributions from upstream basins in the budget calculations
Phosphorus deposited in reservoirs	%	Percentage of average annual total phosphorus load in the basin that is deposited with fine sediment in on-river reservoirs. For internal basins this figure includes the contributions from upstream basins in the budget calculations
Phosphorus delivered to estuaries	%	Percentage of average annual total phosphorus load in the basin that is delivered to estuarine or coastal waters (or to a downstream basin in the case of internal basins). For internal basins this figure includes the contributions from upstream basins in the budget calculations.
Phosphorus—total basin export	t P/yr	Average annual export of total phosphorus from the basin in tonnes per year. For internal basins this figure includes the contributions from upstream basins in the budget calculations.
Phosphorus—export rate	kg P/ha/yr	Average annual total phosphorus areal export rate in kilograms per hectare per year. Contributions from upstream basins are not included in the calculation of this figure, and so some internal basins show as net sinks.
Phosphorus load—times pre-European	ratio	Network-link averaged ratio of average annual total phosphorus load between current and pre-disturbance conditions.
Phosphorus—dissolved to total	ratio	Network-link averaged ratio of average annual dissolved phosphorus load to average annual total phosphorus load.
Nitrogen from sediments	%	Percentage of average annual total nitrogen load that is delivered to the river network in the basin in association with fine sediment.
Nitrogen from point sources	%	Percentage of average annual total nitrogen load that is delivered to the river network in the basin in dissolved forms from urban sewage and industrial discharges.
Nitrogen—dissolved from diffuse sources	%	Percentage of average annual total nitrogen load that is delivered to the river network in the basin in dissolved forms by surface and subsurface run-off.
Nitrogen deposited on floodplain	%	Percentage of average annual total nitrogen load basin that is deposited with fine sediment on river floodplains in the basin. For internal basins this figure includes the contributions from upstream basins in the budget calculations
Nitrogen deposited in reservoirs	%	Percentage of average annual total nitrogen load in the basin that is deposited with fine sediment in on-river reservoirs. For internal basins this figure includes the contributions from upstream basins in the budget calculations

River basin budget attributes

Attribute	Units	Description
Nitrogen—denitrified	%	Percentage of average annual total nitrogen load in the basin that is lost from the river to the atmosphere by denitrification processes. For internal basins this figure includes the contributions from upstream basins in the budget calculations.
Nitrogen delivered to estuary	%	Percentage of average annual total nitrogen load in the basin that is delivered to estuarine or coastal waters (or to a downstream basin in the case of internal basins). For internal basins this figure includes the contributions from upstream basins in the budget calculations.
Nitrogen—total basin export	t/yr	Average annual export of total nitrogen from the basin in tonnes per year. For internal basins this figure includes the contributions from upstream basins in the budget calculations.
Nitrogen—export rate	kg/ha/yr	Average annual total nitrogen areal export rate in kilograms per hectare per year. Contributions from upstream basins are not included in the calculation of this figure, and so some internal basins show as net sinks.
Nitrogen load—times pre-European	ratio	Network-link averaged ratio of average annual total nitrogen load between current and pre-disturbance conditions.
Nitrogen—dissolved to total	ratio	Network-link averaged ratio of average annual dissolved nitrogen load to average annual total nitrogen load.

	Basin number	101	102	103	104	105	106	107	108	109
	Basin name	Jacky Jacky Creek	Olive/ Pascoe Rivers	Lockhart River	Stewart River	Normanby River	Jeannie River	Endeavour River	Daintree River	Mossman River
CONTEXT	Basin area (km^2)	2981	4207	2859	2692	24339	3923	2065	1907	535
	Improved pasture (%)	0.00	0.18	0.08	0.73	0.01	0.29	0.48	0.47	3.98
	Cropping (%)	0.00	0.00	0.00	0.00	0.09	0.00	0.00	2.39	2.80
	Horticulture (%)	0.00	0.00	0.04	0.00	0.00	0.06	0.09	0.06	3.67
	Total agricultural land proportion (%)	0.00	0.18	0.13	0.73	0.09	0.35	0.57	2.92	10.45
CLIMATE	Rain (mm/yr)	1655	1687	1580	1255	1085	1306	1733	2384	1852
	Total evaporation (mm/yr)	839	890	877	730	723	816	982	1188	1073
	Run-off (mm/yr)	816	797	704	525	361	490	752	1196	779
CARBON	Net primary production (tC/ha/yr)	3.4	4.0	5.6	2.9	2.1	3.4	5.7	9.1	7.7
	Plant carbon (tC/ha)	58.5	67.5	96.1	50.6	35.5	57.6	97.2	152.5	131.1
	Litter+soil carbon (tC/ha)	44.0	52.4	97.0	48.8	31.2	44.2	86.8	167.4	131.1
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.30	2.97
	Nitrogen fixation (kg N/ha/yr)	11.39	13.18	18.74	9.80	6.97	11.22	19.08	30.20	27.09
	Total nitrogen (kg N/ha)	3799	4503	8407	4217	2688	3806	7427	14070	11210
	Mineral nitrogen (kg N/ha)	77	85	110	54	49	61	112	224	199
	Mineral nitrogen concentration in soil water (mg N/kg W)	33	35	49	33	27	34	45	57	56
	Nitrogen leached (kg N/ha/yr)	10	11	12	7	5	8	13	23	18
	Nitrogen volatilised (kg N/ha/yr)	2.28	2.64	3.75	1.96	1.38	2.24	3.82	6.04	5.15
	Phosphorus from fertiliser (kg P/ha/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.87
	Total phosphorus (kg P/ha)	741	844	1281	653	489	671	1227	2293	1945
	Dissolved mineral phosphorus (kg P/ha)	14.1	15.6	20.2	10.0	9.0	11.2	20.7	41.2	36.8
	Phosphorus concentration (mg P/kg W)	6.0	6.4	9.0	6.1	5.0	6.3	8.2	10.6	10.2
	Phosphorus leached (kg P/m2/yr)	1.82	1.95	2.20	1.23	0.95	1.51	2.40	4.17	3.24
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	429312	1002222	76457	316955	3898665	499439	608736	112043	18859
	Sediment supply (t/ha/yr)	2.48	2.60	0.38	1.35	1.60	1.93	3.12	0.72	0.59
	Proportion from hillslopes (%)	85.13	79.27	22.48	69.65	88.03	93.85	97.36	81.89	77.52
	Proportion from bank erosion (%)	11.29	18.03	77.25	23.55	3.12	3.86	2.06	17.41	20.85
	Proportion from gullies (%)	3.58	2.70	0.27	6.79	8.84	2.29	0.58	0.71	1.64
	Proportion of length with bed deposition > 0.30 m (proportion)	0.00	0.00	0.00	0.05	0.02	0.00	0.00	0.00	0.00
	Sed Ratio (Euro:pre-Euro) (ratio)	52	46	23	10	3	3	5	4	5
	Sediment export to the coast (t/yr)	329832	712764	37137	160798	1620279	355885	486871	94132	15131
	Specific sediment export to the coast (t/ha/yr)	1.91	1.85	0.18	0.69	0.66	1.37	2.49	0.61	0.48
	River sediment delivery ratio (export/ supply to streams) (ratio)	0.77	0.71	0.49	0.51	0.42	0.71	0.80	0.84	0.80
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	98	97	72	93	97	96	97	84	88
	Phosphorus from point sources (%)	0	0	0	0	0	0	0	0	0
	Phosphorus - dissolved from diffuse sources (%)	2	3	28	7	3	4	3	16	12
	Phosphorus deposited on floodplain (%)	16	19	14	39	49	25	17	4	11
	Phosphorus deposited in reservoirs (%)	0	0	0	0	0	0	0	0	0
	Phosphorus delivered to estuaries (%)	84	81	86	61	51	75	83	96	89
	Phosphorus - total basin export (t P/yr)	223	432	28	49	920	159	228	83	20
	Phosphorus - export rate (kg P/ha/yr)	0.75	1.03	0.10	0.18	0.38	0.43	1.04	0.38	0.31
	Phosphorus load - times pre-European (ratio)	5.5	3.4	2.1	4.1	2.4	1.1	2.8	1.4	2.1
	Phosphorus - dissolved to total (ratio)	19	19	44	11	7	17	20	57	29
	Nitrogen from sediments (%)	91	91	31	70	89	89	88	57	68
	Nitrogen from point sources (%)	0	0	0	0	0	0	0	0	0
	Nitrogen - dissolved from diffuse sources (%)	9	9	69	30	11	11	12	43	32
	Nitrogen deposited on floodplain (%)	16	19	6	28	45	24	16	4	9
	Nitrogen deposited in reservoirs (%)	0	0	0	0	0	0	0	0	0
	Nitrogen – denitrified (%)	0	0	3	3	1	1	0	1	1
	Nitrogen delivered to estuary (%)	84	81	91	69	54	76	83	95	90
	Nitrogen – total export (t/yr)	1243	2875	267	295	4988	1207	1370	684	164
	Nitrogen – export rate (kg/ha/yr)	4.19	6.88	0.89	1.05	2.04	3.28	6.24	3.12	2.57
	Nitrogen load – times pre-European (ratio)	3.0	2.4	1.2	2.0	1.9	1.1	2.2	1.3	1.7
	Nitrogen – dissolved to total (ratio)	28	29	79	43	21	26	30	60	35

110	111	112	113	114	115	116	117	118	119	120	121
Barron River	Mulgrave-Russell River	Johnstone River	Tully River	Murray River (Qld)	Hinchinbrook Island	Herbert River	Black River	Ross River	Haughton River	Burdekin River	Don River
2136	1998	2319	1650	1212	400	9854	1141	1394	4357	130138	3574
6.08	1.57	8.92	0.79	0.98	0.00	0.91	4.43	0.60	0.12	2.02	1.14
1.10	12.85	17.29	3.65	2.62	0.00	5.11	1.65	0.36	8.09	0.65	0.17
4.06	6.13	2.14	0.83	0.51	0.00	0.23	0.73	31.77	11.82	0.05	0.89
11.24	20.55	28.35	5.27	4.11	0.00	6.25	6.81	32.73	20.03	2.71	2.21
1311	3141	3217	2739	2239	2206	1194	1366	977	879	596	840
863	1332	1356	1284	1143	1164	837	923	782	765	549	730
449	1809	1862	1455	1097	1042	357	443	195	143	48	112
5.0	9.4	9.4	8.9	8.6	8.6	4.5	5.7	2.9	3.2	1.9	2.7
84.9	157.1	156.6	148.4	144.3	144.4	77.6	97.1	50.2	54.9	33.7	45.8
98.0	216.4	255.5	183.6	155.2	156.4	78.0	88.4	47.5	55.8	41.0	47.8
1.42	2.56	4.73	2.50	1.75	0.00	1.78	1.87	0.25	3.55	0.54	0.49
20.51	35.76	61.08	29.62	28.64	28.66	17.50	19.04	9.74	10.66	6.79	8.88
8574	17360	21210	14880	12950	13290	6742	7622	4104	4838	3489	4129
143	276	336	258	242	328	121	157	60	68	46	50
46	53	57	52	56	56	45	48	35	39	39	36
10	33	35	24	20	20	10	11	5	7	4	5
3.33	6.29	6.25	5.92	5.73	5.73	3.02	3.81	1.95	2.13	1.30	1.78
0.43	0.65	1.53	0.67	0.53	0.00	0.43	0.09	0.06	0.76	0.07	0.32
1385	2782	3180	2505	2283	2701	1166	1436	661	763	525	614
25.7	49.9	56.1	47.5	44.7	60.4	22.0	28.7	10.9	12.7	8.4	9.3
8.3	9.7	9.6	9.6	10.3	10.3	8.1	8.8	6.5	7.2	7.0	6.7
1.74	5.97	6.10	4.44	3.75	3.66	1.77	2.04	1.00	1.22	0.69	0.88
256782	283721	389552	148375	32243		1300378	120295	206769	697936	18446498	932904
1.19	1.71	1.74	0.85	0.45		1.35	1.71	1.81	1.85	1.42	3.09
79.31	69.56	64.96	32.73	26.66		74.71	91.87	87.63	81.34	66.67	85.82
10.44	28.49	29.26	62.60	65.19		11.75	3.99	3.87	5.49	5.99	3.39
10.25	1.95	5.78	4.67	8.15		13.54	4.14	8.50	13.18	27.34	10.79
0.00	0.04	0.00	0.00	0.00		0.08	0.01	0.00	0.13	0.11	0.04
8	6	29	6	6		8	3	2	10	15	11
145877	222425	305142	88084	17098		664787	82887	58383	172454	2443232	509528
0.68	1.34	1.36	0.51	0.24		0.69	1.18	0.51	0.46	0.19	1.69
0.57	0.78	0.78	0.59	0.53		0.51	0.69	0.28	0.25	0.13	0.55
81	87	94	81	66		97	96	96	98	99	99
15	9	0	0	0		0	0	2	0	0	0
3	4	6	19	34		3	4	2	2	1	1
23	5	4	6	8		32	28	26	66	60	41
9	0	0	0	0		0	0	46	10	22	0
68	95	96	94	92		68	72	28	25	19	59
168	486	430	72	17		702	54	38	137	2538	372
0.72	2.41	1.86	0.42	0.15		0.64	0.50	0.29	0.31	0.19	1.02
3.9	3.7	5.0	1.9	2.1		1.4	2.3	1.3	3.7	5.9	8.0
16	34	37	65	57		13	8	8	5	3	2
76	75	70	52	35		85	88	93	91	91	95
7	4	0	0	0		0	0	1	0	0	0
17	20	30	48	65		15	12	7	9	9	5
23	5	4	5	6		28	25	23	61	53	40
6	0	0	0	0		0	0	39	9	18	0
1	0	0	1	1		1	1	1	1	5	1
70	94	96	94	93		71	75	37	29	24	60
718	2121	1998	617	195		3415	409	269	653	10314	1367
3.08	10.52	8.63	3.59	1.67		3.10	3.79	2.06	1.49	0.79	3.73
2.6	2.5	2.6	1.3	1.4		1.4	2.1	1.4	3.1	3.6	5.5
26	29	37	66	70		21	16	22	15	18	8

	Basin number	122	123	124	125	126	127	128	129	130
	Basin name	Proserpine River	Whitsunday Island	O'Connell River	Pioneer River	Plane Creek	Styx River	Shoalwater Creek	Water Park Creek	Fitzroy River (Qld)
CONTEXT	Basin area (km^2)	2592	257	2373	1584	2545	3062	3873	1867	142677
	Improved pasture (%)	3.26	0.00	4.05	0.11	3.28	1.69	1.26	0.06	9.23
	Cropping (%)	6.84	0.00	10.65	19.84	23.52	1.48	0.00	0.00	3.16
	Horticulture (%)	0.62	0.00	0.09	0.15	0.00	0.13	0.09	0.61	3.11
	Total agricultural land proportion (%)	10.71	0.00	14.80	20.10	26.80	3.30	1.35	0.67	15.50
CLIMATE	Rain (mm/yr)	1339	1673	1569	1471	1420	795	846	1219	632
	Total evaporation (mm/yr)	980	1098	1083	1066	1049	725	759	953	602
	Run off (mm/yr)	369	575	494	428	389	70	90	266	30
CARBON	Net primary production (tC/ha/yr)	5.6	6.9	6.5	6.1	5.5	3.4	3.6	5.2	2.9
	Plant carbon (tC/ha)	94.6	115.9	109.8	104.6	93.3	58.0	61.6	87.8	51.0
	Litter + soil carbon (tC/ha)	93.3	122.2	118.2	106.7	92.2	59.5	60.9	73.6	60.9
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	2.07	0.00	3.71	2.62	4.62	0.51	0.06	0.20	0.79
	Nitrogen fixation (kg N/ha/yr)	18.56	22.87	21.63	20.42	21.47	14.52	13.99	17.34	14.26
	Total nitrogen (kg N/ha)	7920	10250	10070	9104	7845	5156	5279	6248	5276
	Mineral nitrogen (kg N/ha)	90	107	128	177	91	61	67	85	63
	Mineral nitrogen concentration in soil water (mg N/kg W)	46	49	47	45	43	43	43	44	47
	Nitrogen leached (kg N/ha/yr)	11	13	14	14	14	6	6	9	5
	Nitrogen volatilised (kg N/ha/yr)	3.71	4.58	4.33	4.08	3.67	2.25	2.39	3.44	1.94
	Phosphorus from fertiliser (kg P/ha/yr)	0.71	0.00	1.01	0.42	0.70	0.08	0.02	0.03	0.13
	Total phosphorus (kg P/ha)	1149	1414	1494	1637	1127	751	796	1002	750
	Dissolved mineral phosphorus (kg P/ha)	16.7	19.8	23.8	32.5	16.4	10.9	12.2	15.7	11.1
	Phosphorus concentration (mg P/kg W)	8.5	9.0	8.7	8.3	7.8	7.7	7.8	8.1	8.2
	Phosphorus leached (kg P/m2/yr)	2.06	2.42	2.53	2.61	2.49	1.00	1.07	1.66	0.88
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	360226		476556	394058	170267	311714	121338	11823	16360557
	Sediment supply (t/ha/yr)	1.95		2.41	2.33	1.11	1.24	0.46	0.21	1.15
	Proportion from hillslopes (%)	88.13		88.54	85.76	78.13	78.14	57.32	65.11	62.61
	Proportion from bank erosion (%)	6.96		7.57	10.02	13.25	7.58	17.67	14.14	12.70
	Proportion from gullies (%)	4.91		3.90	4.22	8.62	14.28	25.00	20.75	24.69
	Proportion of length with bed deposition > 0.30 m (proportion)	0.07		0.06	0.00	0.00	0.09	0.19	0.00	0.19
	Sed Ratio (Euro:pre-Euro) (ratio)	31		45	28	46	31	12	27	21
	Sediment export to the coast (t/yr)	227314		366309	288343	114860	136011	45166	7940	2635482
	Specific sediment export to the coast (t/ha/yr)	1.23		1.85	1.71	0.75	0.54	0.17	0.14	0.18
	River sediment delivery ratio (export/supply to streams) (ratio)	0.63		0.77	0.73	0.67	0.44	0.37	0.67	0.16
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	97		96	77	91	98	93	70	98
	Phosphorus from point sources (%)	0		0	20	0	0	0	0	0
	Phosphorus - dissolved from diffuse sources (%)	3		4	3	9	2	7	30	2
	Phosphorus deposited on floodplain (%)	31		17	17	21	53	47	12	74
	Phosphorus deposited in reservoirs (%)	0		0	0	0	0	0	0	8
	Phosphorus delivered to estuaries (%)	69		83	83	79	47	53	88	18
	Phosphorus - total basin export (t P/yr)	185		221	276	67	109	45	6	2002
	Phosphorus - export rate (kg P/ha/yr)	0.74		0.89	1.60	0.26	0.35	0.12	0.03	0.14
	Phosphorus load - times pre-European (ratio)	10.7		10.3	7.6	8.8	14.4	2.4	2.7	6.9
	Phosphorus - dissolved to total (ratio)	8		6	10	13	4	30	41	5
	Nitrogen from sediments (%)	82		86	84	64	87	63	30	86
	Nitrogen from point sources (%)	0		0	0	0	0	0	0	0
	Nitrogen - dissolved from diffuse sources (%)	18		14	16	36	13	37	70	14
	Nitrogen deposited on floodplain (%)	28		17	18	16	45	32	6	66
	Nitrogen deposited in reservoirs (%)	0		0	0	0	0	0	0	8
	Nitrogen - denitrified (%)	1		1	2	1	2	4	3	5
	Nitrogen delivered to estuary (%)	71		82	80	83	53	64	91	22
	Nitrogen - total export (t/yr)	637		1277	1073	401	463	220	57	8831
	Nitrogen - export rate (kg/ha/yr)	2.53		5.16	6.22	1.57	1.50	0.59	0.31	0.62
	Nitrogen load - times pre-European (ratio)	4.2		5.3	3.6	3.2	5.0	1.6	1.6	3.3
	Nitrogen - dissolved to total (ratio)	20		15	24	34	18	58	63	25

131 Curtis Island	132 Calliope River	133 Boyne River	134 Baffle Creek	135 Kolan River	136 Burnett River	137 Burrum River	138 Mary River (Qld)	139 Fraser Island	140 Noosa River	141 Maroochy River	142 Pine River
582	2211	2509	4135	2909	33320	3351	9422	1680	1952	1598	1481
0.00	0.51	0.00	4.67	2.33	2.90	2.54	5.13	0.00	1.12	2.72	0.94
0.00	0.05	0.00	0.11	6.26	2.29	8.27	1.68	0.00	0.18	7.70	0.20
27.41	39.60	46.12	0.43	0.67	1.20	3.53	2.86	0.00	7.17	24.53	21.92
27.41	40.17	46.12	5.22	9.26	6.39	14.35	9.67	0.00	8.47	34.95	23.05
806	806	864	1029	860	690	906	1061	1356	1402	1566	1256
738	747	788	897	797	653	819	880	1007	995	1059	961
68	60	77	133	83	40	100	184	350	408	512	295
3.9	4.0	4.9	5.3	4.6	3.7	4.4	6.2	7.6	6.7	7.1	6.1
67.4	69.5	85.0	90.4	78.5	67.4	74.6	111.8	128.2	113.5	121.1	113.5
74.8	76.5	86.8	85.7	77.0	71.1	65.5	109.8	83.4	86.8	112.8	112.2
0.15	0.55	0.31	1.45	0.93	0.79	1.51	1.11	0.00	0.24	4.39	2.07
13.08	13.96	16.23	17.91	16.67	15.94	17.97	30.42	25.31	22.45	23.62	20.28
6494	6647	7481	7334	6639	6170	5666	9426	6759	7070	9164	9449
62	67	71	83	73	73	90	136	115	137	155	130
46	46	50	48	48	50	46	57	58	51	51	50
6	5	6	7	7	6	8	10	15	13	15	10
2.62	2.70	3.25	3.53	3.04	2.46	2.92	4.15	5.06	4.49	4.72	4.06
0.01	0.15	0.03	0.36	0.24	0.19	0.48	0.36	0.00	0.08	0.88	0.48
871	908	1016	1067	953	898	949	1472	1277	1348	1577	1462
11.4	12.3	13.0	15.3	13.4	13.2	16.2	24.0	21.3	25.3	28.7	24.0
8.5	8.5	9.3	8.9	8.8	9.0	8.3	10.2	10.7	9.3	9.4	9.3
1.02	1.00	1.16	1.38	1.29	1.02	1.46	1.84	2.84	2.36	2.75	1.87
	162974	104449	208395	202067	2933214	84291	661576		18546	79989	58966
	0.84	0.42	0.61	0.72	0.87	0.29	0.70		0.15	0.74	0.47
	49.75	30.55	64.50	55.36	44.18	52.86	38.54		9.92	51.89	44.62
	16.44	36.59	14.96	18.99	24.12	27.34	44.43		52.02	28.70	33.93
	33.81	32.86	20.54	25.65	31.70	19.80	17.03		38.07	19.42	21.45
	0.15	0.00	0.04	0.11	0.15	0.00	0.11		0.04	0.00	0.00
	35	8	29	36	96	36	18		15	28	40
	60772	16974	103376	61589	728607	33624	266713		7288	45525	20687
	0.31	0.07	0.30	0.22	0.22	0.11	0.28		0.06	0.42	0.16
	0.37	0.16	0.50	0.30	0.25	0.40	0.40		0.39	0.57	0.35
	96	90	92	94	95	84	85		47	42	83
	0	0	0	0	2	0	6		0	53	0
	4	10	8	6	3	16	9		53	6	17
	48	21	39	33	63	37	37		15	14	15
	0	45	0	26	15	5	1		0	2	29
	52	34	61	41	22	58	62		85	84	56
	56	19	68	48	429	31	229		9	93	17
	0.25	0.07	0.16	0.16	0.13	0.09	0.25		0.04	0.57	0.11
	7.8	2.3	5.0	6.2	6.3	2.8	3.1		1.3	5.1	2.9
	8	25	15	15	8	33	23		66	35	30
	78	60	72	76	82	50	68		15	55	61
	0	0	0	0	1	0	0		0	14	0
	22	40	28	24	18	50	32		85	32	39
	42	17	29	27	54	21	28		5	12	11
	0	32	0	22	12	4	1		0	2	23
	3	5	2	3	6	6	4		4	2	2
	55	47	69	48	28	69	68		91	84	63
	207	147	499	294	2397	262	1638		125	364	179
	0.92	0.58	1.20	1.00	0.72	0.78	1.76		0.58	2.24	1.17
	2.9	1.5	2.4	2.8	3.0	1.8	1.8		1.1	2.3	1.8
	32	56	39	34	32	59	51		86	51	55

	Basin number	143	144	145	146	201	202	203	204	205
	Basin name	Brisbane River	Stradbroke Island	Logan-Albert River	South Coast	Tweed River	Brunswick River	Richmond River	Clarence River	Bellinger River
CONTEXT	Basin area (km^2)	13572	499	4141	1349	1077	508	7020	22284	3461
	Improved pasture (%)	2.02	0.22	2.48	0.31	0.10	0.88	1.37	3.47	1.43
	Cropping (%)	1.37	0.00	1.77	2.43	7.88	3.02	3.14	0.99	0.05
	Horticulture (%)	12.91	21.09	11.24	24.64	14.80	26.86	5.34	0.63	10.44
	Total agricultural land proportion (%)	16.30	21.31	15.49	27.38	22.78	30.75	9.86	5.09	11.92
CLIMATE	Rain (mm/yr)	922	1555	1055	1551	1846	1879	1334	1111	1517
	Total evaporation (mm/yr)	800	1000	862	1043	1105	1131	947	854	993
	Run off (mm/yr)	129	555	199	509	742	752	390	257	525
CARBON	Net primary production (tC/ha/yr)	5.5	4.4	5.8	6.9	8.8	8.0	6.8	7.0	8.6
	Plant carbon (tC/ha)	113.0	75.0	125.1	144.1	192.6	147.2	138.2	213.3	213.1
	Litter + soil carbon (tC/ha)	103.4	50.9	147.1	177.8	256.4	195.6	161.4	208.8	206.5
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	2.79	0.55	2.53	1.13	4.46	2.85	1.74	0.67	0.93
	Nitrogen fixation (kg N/ha/yr)	23.58	14.81	21.59	23.08	29.41	28.28	33.43	35.81	35.54
	Total nitrogen (kg N/ha)	8868	3978	12610	14660	20900	16000	13610	17660	16450
	Mineral nitrogen (kg N/ha)	103	75	130	161	226	213	167	226	192
	Mineral nitrogen concentration in soil water (mg N/kg W)	57	35	55	52	61	55	59	68	68
	Nitrogen leached (kg N/ha/yr)	9	11	9	13	19	16	13	12	17
	Nitrogen volatilised (kg N/ha/yr)	3.68	2.96	3.86	4.62	5.85	5.35	4.57	4.68	5.76
	Phosphorus from fertiliser (kg P/ha/yr)	0.59	0.35	0.32	0.17	0.67	1.66	0.86	0.71	0.65
	Total phosphorus (kg P/ha)	1309	776	1702	2029	2855	2362	1948	2709	2464
	Dissolved mineral phosphorus (kg P/ha)	18.4	13.9	23.7	29.6	41.6	39.6	30.1	40.6	34.8
	Phosphorus concentration (mg P/kg W)	10.2	6.5	9.9	9.5	11.3	10.3	10.5	12.0	12.4
	Phosphorus leached (kg P/m2/yr)	1.62	1.98	1.62	2.41	3.47	3.05	2.25	2.13	3.14
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	1267692		476644	46868	92042	3162	561570	1719721	143423
	Sediment supply (t/ha/yr)	0.93		1.18	0.42	0.87	0.24	0.83	0.78	0.47
	Proportion from hillslopes (%)	54.26		57.86	20.81	52.91	49.17	41.88	24.55	7.05
	Proportion from bank erosion (%)	26.07		24.52	53.78	40.72	35.21	41.33	43.64	64.65
	Proportion from gullies (%)	19.67		17.62	25.41	6.36	15.62	16.79	31.81	28.30
	Proportion of length with bed deposition > 0.30 m (proportion)	0.07		0.19	0.00	0.25	0.00	0.13	0.07	0.08
	Sed Ratio (Euro:pre-Euro) (ratio)	37		35	10	16	5	32	198	101
	Sediment export to the coast (t/yr)	247194		189138	20641	58498	2158	240825	683379	61591
	Specific sediment export to the coast (t/ha/yr)	0.18		0.47	0.19	0.55	0.16	0.36	0.31	0.20
	River sediment delivery ratio (export/ supply to streams) (ratio)	0.19		0.40	0.44	0.64	0.68	0.43	0.40	0.43
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	71		65	20	86	73	90	89	68
	Phosphorus from point sources (%)	25		32	75	0	0	2	0	0
	Phosphorus - dissolved from diffuse sources (%)	4		3	5	14	27	9	11	32
	Phosphorus deposited on floodplain (%)	25		41	11	14	4	30	28	14
	Phosphorus deposited in reservoirs (%)	19		2	2	0	0	0	0	0
	Phosphorus delivered to estuaries (%)	56		56	87	86	96	70	72	86
	Phosphorus - total basin export (t P/yr)	685		265	93	46	3	235	624	54
	Phosphorus - export rate (kg P/ha/yr)	0.50		0.64	0.67	0.42	0.06	0.33	0.28	0.15
	Phosphorus load - times pre-European (ratio)	5.3		4.7	1.4	1.8	2.1	2.9	3.8	2.4
	Phosphorus - dissolved to total (ratio)	17		16	47	40	56	21	20	40
	Nitrogen from sediments (%)	69		78	24	71	43	75	67	34
	Nitrogen from point sources (%)	15		8	48	0	0	0	0	0
	Nitrogen - dissolved from diffuse sources (%)	16		13	28	29	57	25	33	66
	Nitrogen deposited on floodplain (%)	18		39	5	11	4	26	21	7
	Nitrogen deposited in reservoirs (%)	27		0	2	0	0	0	0	0
	Nitrogen - denitrified (%)	3		2	2	1	1	2	3	3
	Nitrogen delivered to estuary (%)	52		59	91	88	96	73	76	90
	Nitrogen - total export (t/yr)	3162		1251	397	499	35	1941	4799	599
	Nitrogen - export rate (kg/ha/yr)	2.33		3.01	2.89	4.58	0.64	2.77	2.16	1.69
	Nitrogen load - times pre-European (ratio)	2.7		3.2	1.5	1.4	1.5	2.3	2.0	1.4
	Nitrogen - dissolved to total (ratio)	37		33	75	55	59	37	49	71

206 Macleay River	207 Hastings River	208 Manning River	209 Karuah River	210 Hunter River	211 Macquarie-Tuggerah Lakes	212 Hawkesbury River	213 Sydney Coast-Georges River	214 Wollongong Coast	215 Shoalhaven River	216 Clyde River - Jervis Bay	217 Moruya River
11396	4530	8174	4375	21454	1575	21956	1742	794	7208	3269	1482
13.58	0.76	2.69	1.49	5.72	0.31	5.73	0.34	1.35	9.35	0.62	3.46
0.48	0.04	0.09	0.00	1.86	0.00	0.43	0.00	0.00	0.50	0.04	0.00
0.19	2.87	3.32	5.14	4.51	33.71	12.87	8.20	21.72	3.80	0.96	0.05
14.26	3.67	6.10	6.63	12.09	34.01	19.03	8.54	23.07	13.65	1.62	3.51
980	1352	1079	1151	784	1156	903	1053	1329	876	1062	906
780	940	826	805	671	847	705	778	866	655	755	694
201	413	254	347	118	309	199	277	464	221	307	212
6.7	8.2	7.9	7.1	5.4	7.1	6.1	4.1	6.3	6.4	7.5	7.0
255.0	230.7	277.5	168.4	160.8	169.8	224.1	102.1	178.3	268.2	255.6	275.9
235.3	256.5	289.4	162.2	159.7	145.5	189.9	86.6	202.0	235.5	240.6	288.1
1.47	0.31	0.48	0.29	1.03	1.24	0.62	0.69	1.31	0.73	0.40	0.08
56.20	30.34	37.10	28.95	35.66	24.76	36.77	14.09	26.32	48.81	27.56	34.91
19780	21120	24460	13570	13740	11970	15930	7189	16630	19890	20150	24560
180	234	285	181	155	172	185	115	209	193	203	196
78	68	77	65	69	65	74	45	58	85	78	81
13	15	13	12	9	12	11	8	12	12	13	11
4.49	5.46	5.30	4.71	3.60	4.70	4.08	2.74	4.17	4.25	5.03	4.65
1.87	0.53	0.80	0.40	0.99	1.05	0.80	0.40	1.15	1.15	0.42	0.38
2667	3026	3592	2104	1964	1974	2400	1228	2484	2810	2867	3139
29.9	43.2	51.3	33.0	26.8	32.1	32.2	21.3	38.1	33.0	37.3	34.8
13.0	12.5	13.9	11.9	11.9	12.2	12.7	8.3	10.7	14.3	14.3	14.4
2.12	2.75	2.35	2.20	1.57	2.23	1.88	1.39	2.23	2.05	2.44	1.97
1028976	189596	533797	175415	2950924	37218	1125630	37449	21043	407591	88581	60453
0.90	0.45	0.67	0.48	1.40	0.27	0.52	0.25	0.43	0.57	0.33	0.40
29.67	6.53	14.53	15.73	33.42	10.70	21.46	6.54	12.34	13.88	4.72	14.32
29.48	69.70	46.64	40.00	20.35	30.35	28.47	53.04	20.93	26.04	27.69	19.47
40.84	23.77	38.83	44.27	46.23	58.95	50.07	40.42	66.73	60.08	67.59	66.21
0.13	0.09	0.03	0.15	0.33	0.32	0.08	0.09	0.00	0.10	0.18	0.10
65	332	56	161	630	111	211	323	3	27	20	44
345455	83255	224159	72363	743606	13915	233011	11226	8904	135530	34173	24362
0.30	0.20	0.28	0.20	0.35	0.10	0.11	0.07	0.18	0.19	0.13	0.16
0.34	0.44	0.42	0.41	0.25	0.37	0.21	0.30	0.42	0.33	0.39	0.40
91	71	83	79	97	70	78	72	72	78	66	82
0	0	0	0	0	0	11	0	0	9	0	0
9	29	17	21	3	30	11	28	28	13	34	18
39	13	19	23	49	23	27	35	7	30	21	27
2	0	0	0	5	0	26	0	12	0	0	0
59	87	81	77	46	77	47	65	81	70	79	73
319	71	176	60	891	15	344	10	7	161	30	23
0.28	0.16	0.22	0.13	0.42	0.09	0.16	0.05	0.09	0.23	0.09	0.15
4.8	2.4	2.7	3.1	4.6	2.4	2.4	2.3	1.3	2.6	1.7	3.4
13	41	20	29	9	33	26	35	35	20	33	18
76	33	55	50	83	36	55	40	41	57	29	48
0	0	0	0	0	0	11	0	0	2	0	0
24	67	45	50	17	64	34	60	59	41	71	52
33	6	12	16	41	11	17	19	4	20	8	15
1	0	0	0	6	0	19	0	6	0	0	0
3	4	4	3	3	3	6	5	2	4	4	4
63	91	84	81	50	85	59	76	88	77	88	81
2944	686	1546	571	4444	162	3234	114	82	1256	348	205
2.59	1.52	1.89	1.29	2.07	1.02	1.47	0.64	1.00	1.75	1.03	1.35
3.1	1.3	1.7	1.6	2.7	1.4	1.7	1.4	1.0	1.7	1.2	1.7
31	76	59	59	33	70	59	68	68	56	78	57

	Basin number	218	219	220	221	222	223	224	225	226
	Basin name	Tuross River	Bega River	Towamba River	East Gippsland	Snowy River	Tambo River	Mitchell River	Thomson River	Latrobe River
CONTEXT	Basin area (km^2)	2166	2838	2193	5648	15772	4217	4866	6413	4681
	Improved pasture (%)	6.43	2.36	0.72	0.50	9.26	4.02	3.29	6.94	22.11
	Cropping (%)	0.37	0.19	0.00	0.00	0.46	0.00	0.19	0.26	0.39
	Horticulture (%)	0.73	6.52	0.89	0.95	1.57	4.81	1.29	0.10	11.36
	Total agricultural land proportion (%)	7.53	9.07	1.61	1.45	11.28	8.82	4.77	7.30	33.86
CLIMATE	Rain (mm/yr)	887	871	879	960	821	774	984	873	958
	Total evaporation (mm/yr)	681	672	660	662	567	571	587	555	576
	Run off (mm/yr)	207	204	220	298	253	203	397	327	387
CARBON	Net primary production (tC/ha/yr)	6.9	6.7	6.9	7.9	5.8	6.9	6.7	6.5	6.6
	Plant carbon (tC/ha)	295.7	275.0	282.6	324.3	348.4	347.5	423.5	369.0	312.0
	Litter + soil carbon (tC/ha)	310.4	295.9	284.4	322.1	368.0	338.2	420.2	358.3	335.1
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.47	1.58	0.24	0.03	0.25	0.08	0.14	1.41	2.04
	Nitrogen fixation (kg N/ha/yr)	47.08	30.65	25.67	28.25	44.33	23.88	22.40	33.67	45.20
	Total nitrogen (kg N/ha)	26580	25280	24030	27500	31380	29040	35440	30540	28820
	Mineral nitrogen (kg N/ha)	211	193	184	276	212	204	235	226	255
	Mineral nitrogen concentration in soil water (mg N/kg W)	87	81	82	91	88	93	87	95	97
	Nitrogen leached (kg N/ha/yr)	12	11	11	13	11	11	14	13	14
	Nitrogen volatilised (kg N/ha/yr)	4.60	4.49	4.61	5.24	3.86	4.57	4.48	4.36	4.43
	Phosphorus from fertiliser (kg P/ha/yr)	0.65	1.30	0.33	0.06	0.58	0.47	0.35	1.92	3.85
	Total phosphorus (kg P/ha)	3352	3197	3096	3912	3833	3747	4541	4027	3929
	Dissolved mineral phosphorus (kg P/ha)	35.7	35.3	33.8	50.7	35.6	37.9	43.6	41.4	47.5
	Phosphorus concentration (mg P/kg W)	14.7	14.7	15.1	16.8	14.7	17.2	16.2	17.2	17.5
	Phosphorus leached (kg P/m2/yr)	2.05	1.97	1.94	2.47	1.90	1.99	2.50	2.41	2.61
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	70126	125308	67504	64810	813701	59536	70209	114798	123369
	Sediment supply (t/ha/yr)	0.37	0.50	0.40	0.13	0.53	0.14	0.15	0.18	0.24
	Proportion from hillslopes (%)	6.54	8.52	4.22	6.05	20.58	9.23	11.11	6.08	5.93
	Proportion from bank erosion (%)	21.59	30.54	29.43	47.37	26.34	59.12	85.42	80.88	92.44
	Proportion from gullies (%)	71.87	60.94	66.35	46.57	53.08	31.65	3.47	13.04	1.63
	Proportion of length with bed deposition > 0.30 m (proportion)	0.13	0.12	0.04	0.01	0.04	0.02	0.02	0.01	0.08
	Sed Ratio (Euro:pre-Euro) (ratio)	41	191	48	36	16	19	3	108	5
	Sediment export to the coast (t/yr)	23959	40908	26302	25818	303309	18114	25330	23583	31953
	Specific sediment export to the coast (t/ha/yr)	0.13	0.16	0.15	0.05	0.20	0.04	0.05	0.04	0.06
	River sediment delivery ratio (export/ supply to streams) (ratio)	0.34	0.33	0.39	0.40	0.37	0.30	0.36	0.21	0.26
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	74	79	72	40	85	50	45	47	42
	Phosphorus from point sources (%)	0	0	0	0	0	0	0	0	7
	Phosphorus - dissolved from diffuse sources (%)	26	21	28	60	15	50	55	53	51
	Phosphorus deposited on floodplain (%)	31	30	22	15	35	42	24	37	81
	Phosphorus deposited in reservoirs (%)	0	6	0	0	0	0	0	15	3
	Phosphorus delivered to estuaries (%)	69	64	78	85	65	58	76	48	16
	Phosphorus - total basin export (t P/yr)	21	30	19	35	250	19	33	28	8
	Phosphorus - export rate (kg P/ha/yr)	0.10	0.10	0.09	0.06	0.16	0.33	0.03	0.05	0.01
	Phosphorus load - times pre-European (ratio)	2.2	2.7	2.5	1.3	2.1	1.3	1.0	1.1	1.3
	Phosphorus - dissolved to total (ratio)	20	19	19	55	30	51	63	58	43
	Nitrogen from sediments (%)	35	44	36	14	54	21	19	19	16
	Nitrogen from point sources (%)	0	0	0	0	0	0	0	0	10
	Nitrogen - dissolved from diffuse sources (%)	65	56	64	86	46	79	81	81	74
	Nitrogen deposited on floodplain (%)	12	15	9	3	20	11	7	8	14
	Nitrogen deposited in reservoirs (%)	0	3	0	0	0	0	0	3	1
	Nitrogen - denitrified (%)	7	4	5	5	5	12	9	9	23
	Nitrogen delivered to estuary (%)	81	78	86	91	75	76	85	80	62
	Nitrogen - total export (t/yr)	229	305	202	571	2230	347	552	670	457
	Nitrogen - export rate (kg/ha/yr)	1.05	1.06	0.90	1.01	1.42	5.86	0.48	1.13	0.54
	Nitrogen load - times pre-European (ratio)	1.5	1.5	1.4	1.1	1.6	1.1	1.0	1.1	1.2
	Nitrogen - dissolved to total (ratio)	69	64	67	89	59	87	90	90	89

227 South Gippsland	228 Bunyip River	229 Yarra River	230 Maribyrnong River	231 Werribee River	232 Moorabool River	233 Barwon River	234 Lake Corangamite	235 Otway Coast	236 Hopkins River	237 Portland Coast	238 Glenelg River
6777	4077	4118	1456	1970	2229	3798	4087	3879	10079	3957	12128
33.89	15.58	4.97	18.41	12.98	28.92	26.60	34.43	28.46	34.99	41.45	38.51
0.13	0.31	0.02	1.00	5.66	5.28	4.20	8.08	0.20	6.37	1.14	1.80
0.72	28.21	25.41	20.42	13.50	12.29	6.90	1.73	2.55	6.10	9.87	0.23
34.74	44.09	30.41	39.83	32.14	46.49	37.71	44.24	31.21	47.46	52.46	40.54
898	908	1049	681	641	610	666	640	1019	644	726	664
546	562	588	466	464	457	452	426	534	432	441	410
354	351	462	214	179	153	214	217	486	212	285	256
6.0	5.2	5.9	3.9	4.2	3.9	4.0	3.6	5.8	3.7	4.2	3.9
256.4	205.9	280.1	193.2	203.0	177.9	170.4	154.5	249.3	163.9	173.2	166.7
234.1	215.8	298.3	221.7	209.7	175.3	158.6	150.3	214.1	160.0	154.4	164.7
1.72	2.65	0.66	0.23	1.92	1.81	1.42	2.33	3.04	1.66	0.89	0.57
48.82	17.34	19.79	41.76	20.96	49.58	26.82	19.64	19.48	29.55	52.04	44.14
20230	18620	25370	19470	18180	15160	13620	13020	17750	13840	13380	14360
232	162	201	161	134	127	116	119	158	117	142	153
98	72	77	85	79	90	80	76	83	87	96	97
14	11	13	9	9	9	9	9	14	10	12	11
4.02	3.46	3.96	2.63	2.78	2.60	2.64	2.40	3.86	2.46	2.77	2.61
4.74	3.77	0.94	0.84	1.52	2.28	2.29	4.06	4.35	3.89	4.39	2.66
3095	2550	3326	2390	2327	1944	1850	1850	2583	1894	1932	2009
43.3	32.7	37.7	25.3	24.5	20.0	21.0	24.1	32.1	22.3	24.2	24.8
17.5	14.5	14.5	13.5	14.5	14.4	14.6	15.1	17.0	16.0	16.4	16.0
2.57	2.12	2.46	1.42	1.59	1.48	1.62	1.76	2.72	1.75	1.97	1.80
104425	64453	133746	75049	53505	71993	114202	53076	54651	444368	63559	700985
0.22	0.24	0.33	0.52	0.29	0.37	0.35	0.26	0.18	0.50	0.18	0.60
15.23	6.33	2.78	8.09	23.10	12.47	7.49	7.91	11.30	2.86	4.30	2.20
84.77	82.66	78.25	57.09	45.98	39.16	59.40	40.50	82.21	43.97	78.83	29.92
0.00	11.02	18.97	34.82	30.92	48.37	33.11	51.59	6.48	53.17	16.87	67.88
0.01	0.00	0.00	0.00	0.01	0.04	0.13	0.12	0.09	0.22	0.04	0.38
15	>1,000	7	10	9	70	35	53	16	198	>1,000	309
41644	21882	37091	26644	8885	16766	23601	0	22950	64382	19143	147721
0.09	0.08	0.09	0.19	0.05	0.09	0.07	0.00	0.08	0.07	0.05	0.13
0.40	0.34	0.28	0.36	0.17	0.23	0.21	0.00	0.42	0.14	0.30	0.21
53	56	62	85	73	78	74	67	51	79	57	81
0	0	0	0	0	0	0	0	0	0	0	0
47	44	38	15	27	22	26	33	49	21	43	19
22	27	35	35	30	33	60	54	20	63	30	51
0	0	0	0	35	10	0	0	0	0	0	3
78	73	65	65	35	57	40	46	80	37	70	46
40	22	35	17	8	15	17	10	27	55	22	102
0.06	0.05	0.06	0.12	0.04	0.14	0.03	0.03	0.07	0.05	0.06	0.07
1.5	1.3	1.3	2.0	1.1	1.6	1.9	1.9	1.5	2.3	1.8	2.1
38	43	45	22	23	22	28	23	44	20	31	21
27	26	25	32	47	44	41	33	28	44	20	44
0	0	7	38	0	0	0	0	0	0	0	0
73	74	68	30	53	56	59	67	72	56	80	56
8	10	11	12	16	17	28	22	7	32	8	24
0	0	0	0	20	4	0	0	0	0	0	1
6	5	5	10	9	9	10	13	4	11	8	10
86	86	84	78	56	71	62	65	89	57	84	65
615	296	541	271	136	187	245	151	408	672	337	1174
0.93	0.75	0.97	1.87	0.64	1.84	0.47	0.38	1.05	0.67	0.83	0.86
1.4	1.2	1.1	1.7	1.4	2.0	1.5	1.8	1.2	1.9	1.5	1.7
78	84	86	68	70	66	68	71	75	64	81	65

	Basin number	239	301	302	303	304	305	306	307	308
	Basin name	Millicent Coast	Flinders Cape Barren Islands	East Coast	Coal River	Derwent River	Kingston Coast	Huon River	South-West Coast	Gordon River
CONTEXT	Basin area (km^2)	34346	2005	6945	684	9832	746	3008	5488	5917
	Improved pasture (%)	41.34	12.18	9.93	17.56	11.70	8.51	2.26	0.16	0.00
	Cropping (%)	9.00	0.14	0.54	0.98	0.65	0.16	0.00	0.00	0.00
	Horticulture (%)	2.67	0.05	0.68	5.61	1.61	11.64	5.59	0.57	0.00
	Total agricultural land proportion (%)	53.01	12.37	11.15	24.15	13.96	20.31	7.85	0.73	0.00
CLIMATE	Rain (mm/yr)	533	703	742	560	1005	874	1497	2035	2325
	Total evaporation (mm/yr)	352	474	492	406	469	507	584	633	663
	Run off (mm/yr)	186	229	250	154	537	367	914	1401	1662
CARBON	Net primary production (tC/ha/yr)	2.8	4.1	5.3	3.8	4.3	4.9	4.6	3.5	4.1
	Plant carbon (tC/ha)	102.6	172.8	281.0	226.6	342.0	278.9	320.6	228.4	293.8
	Litter + soil carbon (tC/ha)	115.1	128.4	262.5	201.1	357.4	258.0	350.9	242.3	367.0
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	1.03	0.04	0.44	0.33	0.61	0.50	0.11	0.01	0.00
	Nitrogen fixation (kg N/ha/yr)	65.48	13.78	40.11	19.62	15.49	17.60	20.77	12.10	13.60
	Total nitrogen (kg N/ha)	9954	11020	22610	17280	29500	21420	26620	16680	25960
	Mineral nitrogen (kg N/ha)	149	123	210	112	188	132	173	159	206
	Mineral nitrogen concentration in soil water (mg N/kg W)	114	70	95	81	72	76	64	43	45
	Nitrogen leached (kg N/ha/yr)	12	9	11	7	11	10	14	16	19
	Nitrogen volatilised (kg N/ha/yr)	1.89	2.76	3.55	2.56	2.88	3.28	3.07	2.34	2.72
	Phosphorus from fertiliser (kg P/ha/yr)	2.45	1.05	1.60	1.16	1.96	1.44	0.26	0.02	0.00
	Total phosphorus (kg P/ha)	1433	1764	3116	2233	3733	2710	3345	2428	3466
	Dissolved mineral phosphorus (kg P/ha)	19.8	23.5	36.1	20.3	35.9	25.2	31.1	29.0	37.6
	Phosphorus concentration (mg P/kg W)	15.1	13.3	16.3	14.8	14.2	14.5	11.3	7.7	8.2
	Phosphorus leached (kg P/m2/yr)	1.54	1.65	1.90	1.31	2.07	1.91	2.46	2.82	3.40
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	57265		87713	32163	351478	1099	112375	193822	276625
	Sediment supply (t/ha/yr)	0.16		0.20	0.55	0.37	0.09	0.38	0.55	0.52
	Proportion from hillslopes (%)	3.89		24.46	34.08	13.13	31.92	6.99	4.63	1.93
	Proportion from bank erosion (%)	81.53		35.29	22.78	64.98	36.04	82.20	95.33	94.78
	Proportion from gullies (%)	14.58		40.24	43.14	21.89	32.04	10.81	0.04	3.29
	Proportion of length with bed deposition > 0.30 m (proportion)	0.06		0.01	0.09	0.03	0.00	0.00	0.03	0.00
	Sed Ratio (Euro:pre-Euro) (ratio)	77		5	11	47	3	16	9	186
	Sediment export to the coast (t/yr)	0		44400	15544	149437	727	57413	99086	127593
	Specific sediment export to the coast (t/ha/yr)	0.00		0.10	0.27	0.16	0.06	0.19	0.28	0.24
	River sediment delivery ratio (export/ supply to streams) (ratio)	0.00		0.51	0.48	0.43	0.66	0.51	0.51	0.46
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	54		67	89	68	41	73	77	69
	Phosphorus from point sources (%)	0		0	0	12	0	0	0	0
	Phosphorus - dissolved from diffuse sources (%)	46		33	11	20	59	27	23	31
	Phosphorus deposited on floodplain (%)	48		13	26	7	0	1	1	4
	Phosphorus deposited in reservoirs (%)	0		0	0	9	0	0	0	2
	Phosphorus delivered to estuaries (%)	52		87	74	85	100	99	99	94
	Phosphorus - total basin export (t P/yr)	14		46	11	169	1	52	90	117
	Phosphorus - export rate (kg P/ha/yr)	0.00		0.07	0.15	0.17	0.02	0.15	0.16	0.21
	Phosphorus load - times pre-European (ratio)	1.7		1.4	4.4	1.4	1.3	1.7	1.3	0.8
	Phosphorus - dissolved to total (ratio)	24		42	10	59	63	72	68	75
	Nitrogen from sediments (%)	17		35	74	43	23	37	39	29
	Nitrogen from point sources (%)	0		0	0	7	0	0	0	0
	Nitrogen - dissolved from diffuse sources (%)	83		65	26	50	77	63	61	71
	Nitrogen deposited on floodplain (%)	10		6	20	5	0	1	1	2
	Nitrogen deposited in reservoirs (%)	0		0	0	6	0	0	0	5
	Nitrogen - denitrified (%)	16		2	1	1	1	1	1	2
	Nitrogen delivered to estuary (%)	74		92	79	88	99	99	98	91
	Nitrogen - total export (t/yr)	301		565	105	1435	15	478	750	1075
	Nitrogen - export rate (kg/ha/yr)	0.10		0.82	1.50	1.47	0.36	1.42	1.37	1.92
	Nitrogen load - times pre-European (ratio)	2.0		1.3	2.7	1.2	1.1	1.3	1.2	0.9
	Nitrogen - dissolved to total (ratio)	83		65	27	72	77	72	65	87

309	310	311	312	313	314	315	316	317	318	319	401
King-Henty Rivers	Pieman River	Sandy Cape Coast	Arthur River	King Island	Smithton-Burnie Coast	Forth River	Mersey River	Rubicon River	Tamar River	Piper-Ringarooma Rivers	Upper Murray River
1796	4156	874	2498	1086	4660	1129	1968	678	11344	3549	15338
0.11	0.08	0.60	0.93	34.18	18.40	2.65	19.04	15.39	21.51	15.57	7.60
0.00	0.00	0.00	0.02	0.00	0.34	0.43	0.98	1.16	2.35	0.10	0.67
0.11	1.14	0.00	1.23	0.44	9.54	13.31	7.66	12.50	2.56	3.67	0.11
0.21	1.22	0.60	2.18	34.62	28.29	16.39	27.68	29.04	26.42	19.34	8.39
2509	2148	1627	1694	926	1250	1905	1407	881	803	918	1119
688	658	598	607	472	541	624	571	480	459	505	615
1821	1490	1029	1087	454	713	1287	850	411	347	416	505
4.3	4.4	4.3	5.5	5.1	6.1	5.7	6.3	6.4	5.3	6.1	6.2
279.9	310.2	228.4	335.1	219.2	334.8	445.2	430.5	334.4	350.3	315.5	378.7
483.3	452.5	200.2	402.0	146.3	368.2	548.2	516.1	318.9	357.2	318.6	370.0
0.19	0.07	0.04	0.12	0.43	2.77	1.53	3.53	4.44	1.37	1.15	0.34
14.43	14.65	16.20	21.29	16.97	67.17	24.23	82.70	58.71	61.11	28.12	31.91
36330	34890	15570	33010	12350	31850	42640	43300	27940	30900	27610	31000
240	249	171	318	156	348	268	359	254	250	226	211
47	50	55	69	82	105	71	110	118	114	95	81
18	17	16	18	14	21	20	21	17	14	14	14
2.89	2.93	2.88	3.70	3.39	4.09	3.79	4.19	4.26	3.56	4.06	4.15
0.37	0.13	0.11	0.33	5.69	6.11	1.88	6.28	8.56	3.73	3.52	0.77
4283	4258	2359	4489	2211	4537	5264	5516	3972	4051	3787	3975
44.0	45.6	31.0	58.3	33.3	60.8	50.0	59.8	48.6	42.1	43.3	37.8
8.6	9.2	10.1	12.7	17.5	18.2	13.3	18.2	22.4	18.6	18.4	14.4
3.33	3.12	2.96	3.24	3.10	3.56	3.64	3.57	3.26	2.41	2.68	2.57
8337	37039	5570	38779		70736	16957	106546	15023	463606	85848	726767
0.05	0.09	0.31	0.16		0.21	0.15	0.56	0.34	0.42	0.28	0.45
24.00	12.04	0.62	4.19		6.09	12.18	5.89	2.62	8.74	4.56	22.93
75.74	86.21	99.38	93.52		86.23	49.40	56.12	36.62	70.30	48.75	45.49
0.26	1.75	0.00	2.29		7.68	38.41	37.99	60.75	20.96	46.68	31.58
0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.07	0.00	0.03
96	138	102	36		27	1	6	12	6	7	8
4903	16698	2712	19726		34941	6339	51007	7020	195373	39746	2783
0.03	0.04	0.15	0.08		0.10	0.06	0.27	0.16	0.18	0.13	0.00
0.59	0.45	0.49	0.51		0.49	0.37	0.48	0.47	0.42	0.46	0.00
57	46	55	46		48	52	63	58	53	47	78
0	6	0	0		0	0	11	0	31	18	0
43	49	45	54		52	48	26	42	17	35	22
4	0	1	1		2	0	3	5	11	6	11
0	1	0	0		0	6	1	0	1	0	71
96	99	99	99		98	94	96	95	88	94	18
24	49	3	30		47	16	49	6	277	45	70
0.13	0.12	0.03	0.12		0.11	0.14	0.25	0.10	0.24	0.13	0.05
2.1	1.5	1.9	1.3		1.4	0.6	0.8	1.8	1.6	1.9	1.2
74	97	72	89		69	93	73	40	37	48	41
20	17	19	17		15	18	29	21	33	25	51
0	0	0	0		5	0	4	0	14	0	0
80	83	81	83		80	82	66	79	53	75	49
2	0	1	0		1	0	1	2	7	3	6
0	8	0	0		0	9	2	0	1	0	42
4	1	0	1		1	1	1	1	2	2	2
94	91	99	99		98	90	96	97	91	95	51
280	581	32	421		715	189	469	80	2182	443	1920
1.55	1.38	0.37	1.68		1.60	1.68	2.34	1.21	1.92	1.24	1.32
1.2	1.1	1.2	1.1		1.3	0.9	0.9	1.4	1.5	1.2	1.2
82	89	82	81		82	90	80	77	66	75	70

	Basin number	402	403	404	405	406	407	408	409	410
	Basin name	Kiewa River	Ovens River	Broken River	Goulburn River	Campaspe River	Loddon River	Avoca River	Murray-Riverina	Murrumbidgee River
CONTEXT	Basin area (km^2)	1916	7986	7091	16853	4057	15648	14192	15055	81646
	Improved pasture (%)	13.87	13.85	31.60	22.75	29.68	28.57	16.52	11.13	9.44
	Cropping (%)	0.00	3.26	11.33	3.26	7.90	13.22	30.41	17.34	14.99
	Horticulture (%)	0.40	1.01	3.38	2.79	4.73	4.31	7.31	1.67	1.48
	Total agricultural land proportion (%)	14.26	18.12	46.30	28.79	42.31	46.10	54.24	30.14	25.91
CLIMATE	Rain (mm/yr)	1232	1027	605	849	600	475	365	399	565
	Total evaporation (mm/yr)	622	569	469	509	427	412	322	398	454
	Run off (mm/yr)	612	463	189	367	200	118	59	59	129
CARBON	Net primary production (tC/ha/yr)	5.9	5.3	3.8	4.8	3.4	3.0	2.0	2.8	3.4
	Plant carbon (tC/ha)	321.0	260.9	141.1	233.7	144.8	109.3	63.7	84.8	138.3
	Litter + soil carbon (tC/ha)	332.6	261.2	157.1	239.8	160.3	139.4	89.9	121.4	152.3
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.46	0.43	3.32	1.11	1.10	1.19	2.23	3.19	3.04
	Nitrogen fixation (kg N/ha/yr)	24.93	21.06	23.52	36.97	40.50	26.80	30.15	40.99	41.89
	Total nitrogen (kg N/ha)	27790	22210	13530	20480	13860	12050	7504	10410	13020
	Mineral nitrogen (kg N/ha)	172	156	105	157	111	104	75	112	125
	Mineral nitrogen concentration in soil water (mg N/kg W)	74	74	76	86	84	78	98	92	89
	Nitrogen leached (kg N/ha/yr)	14	13	9	12	9	8	10	9	11
	Nitrogen volatilised (kg N/ha/yr)	3.91	3.54	2.51	3.17	2.28	1.97	1.32	1.87	2.24
	Phosphorus from fertiliser (kg P/ha/yr)	1.40	1.00	3.39	1.79	2.12	2.19	2.94	2.22	2.09
	Total phosphorus (kg P/ha)	3454	2861	1763	2651	1750	1540	988	1347	1719
	Dissolved mineral phosphorus (kg P/ha)	31.8	28.8	19.9	27.4	18.1	18.4	12.4	17.4	20.0
	Phosphorus concentration (mg P/kg W)	13.8	13.8	14.4	14.6	13.8	13.6	16.0	14.2	14.0
	Phosphorus leached (kg P/m2/yr)	2.62	2.35	1.72	2.11	1.48	1.36	1.59	1.36	1.67
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	107968	422132	236215	968068	443827	875014	478643	1094539	4665626
	Sediment supply (t/ha/yr)	0.56	0.52	0.49	0.60	1.12	0.73	0.80	1.04	0.74
	Proportion from hillslopes (%)	13.23	9.66	6.32	8.03	2.76	3.13	4.40	1.49	12.39
	Proportion from bank erosion (%)	61.84	50.26	44.61	44.90	17.58	25.08	15.98	88.05	36.13
	Proportion from gullies (%)	24.93	40.07	49.07	47.06	79.66	71.79	79.62	10.46	51.48
	Proportion of length with bed deposition > 0.30 m (proportion)	0.00	0.09	0.22	0.19	0.52	0.47	0.55	0.25	0.34
	Sed Ratio (Euro:pre-Euro) (ratio)	3	24	17	11	23	44	40	103	434
	Sediment export to the coast (t/yr)	4582	15788	6635	46712	10690	4459	0	101001	109163
	Specific sediment export to the coast (t/ha/yr)	0.02	0.02	0.01	0.03	0.03	0.00	0.00	0.10	0.02
	River sediment delivery ratio (export/ supply to streams) (ratio)	0.04	0.04	0.03	0.05	0.02	0.01	0.00	0.09	0.02
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	68	74	84	74	91	90	0	88	89
	Phosphorus from point sources (%)	15	8	0	5	0	0	0	2	0
	Phosphorus - dissolved from diffuse sources (%)	17	18	16	20	9	10	0	10	11
	Phosphorus deposited on floodplain (%)	14	29	65	45	37	67	0	84	62
	Phosphorus deposited in reservoirs (%)	0	2	5	9	32	26	0	45	25
	Phosphorus delivered to estuaries (%)	86	69	31	46	30	7	0	188	13
	Phosphorus - total basin export (t P/yr)	52	149	35	144	41	14	0	438	243
	Phosphorus - export rate (kg P/ha/yr)	0.18	0.17	0.20	0.05	0.10	0.01	0.00	-0.09	0.03
	Phosphorus load - times pre-European (ratio)	1.1	1.1	1.7	1.7	0.7	2.3	2.7	1.3	2.3
	Phosphorus - dissolved to total (ratio)	34	36	18	30	17	12	8	20	12
	Nitrogen from sediments (%)	50	47	47	48	66	64	0	60	56
	Nitrogen from point sources (%)	0	3	0	2	0	0	0	2	6
	Nitrogen - dissolved from diffuse sources (%)	50	51	53	51	34	36	0	38	38
	Nitrogen deposited on floodplain (%)	8	16	30	24	25	44	0	51	35
	Nitrogen deposited in reservoirs (%)	0	1	3	5	23	18	0	27	16
	Nitrogen - denitrified (%)	1	3	6	3	3	8	0	21	9
	Nitrogen delivered to estuary (%)	91	81	61	68	48	30	0	437	40
	Nitrogen - total export (t/yr)	406	1360	426	1961	400	370	0	6859	5409
	Nitrogen - export rate (kg/ha/yr)	1.38	1.53	2.40	0.72	1.00	0.26	0.00	0.02	0.63
	Nitrogen load - times pre-European (ratio)	1.0	1.1	1.6	1.4	1.8	1.9	2.9	1.7	2.3
	Nitrogen - dissolved to total (ratio)	62	71	66	64	56	57	59	81	58

411 Lake George	412 Lachlan River	413 Benanee	414 Mallee	415 Wimmera – Avon Rivers	416 Border Rivers	417 Moonie River	418 Gwydir River	419 Namoi River	420 Castlereagh River	421 Macquarie-Bogan Rivers	422 Condamine-Culgoa Rivers
945	90863	21349	41494	30369	48034	14335	26588	42004	17411	74803	162602
13.98	10.57	0.28	6.49	14.59	3.58	1.67	4.72	5.89	6.91	10.60	3.22
1.36	11.72	1.61	17.04	28.38	16.10	12.58	17.24	11.49	12.77	13.98	6.09
0.06	0.62	0.30	1.74	9.81	2.57	0.33	3.70	2.49	0.32	1.18	1.05
15.40	22.91	2.19	25.27	52.78	22.24	14.58	25.67	19.87	19.99	25.76	10.35
718	482	285	306	408	667	566	662	659	576	548	514
478	424	274	276	319	628	547	617	598	527	495	496
240	62	12	34	89	48	21	58	71	49	57	20
3.3	2.6	1.2	1.5	2.1	3.5	2.5	3.4	3.6	2.9	2.9	2.1
167.1	81.2	31.2	42.3	76.5	88.0	43.2	92.9	100.9	72.2	86.2	39.8
153.7	96.6	62.8	64.7	112.6	97.7	55.2	105.3	113.8	97.1	100.0	52.2
0.61	1.82	0.42	1.10	2.44	3.26	2.64	3.29	2.78	1.43	1.66	1.50
20.72	37.05	5.02	17.03	33.12	32.24	18.74	35.47	37.12	31.98	39.12	13.23
13160	8243	5103	5239	9607	8503	4778	9179	9899	8482	8644	4486
71	101	41	52	108	108	74	114	116	114	108	63
54	78	59	77	98	61	53	62	64	67	73	49
6	8	3	6	10	9	6	9	8	8	8	5
2.21	1.74	0.83	0.97	1.41	2.34	1.63	2.29	2.39	1.96	1.92	1.40
0.94	1.41	0.27	1.06	2.64	0.75	0.26	0.89	0.68	0.49	1.08	0.20
1594	1144	619	691	1273	1183	714	1257	1337	1170	1190	657
12.5	15.5	7.5	8.5	17.2	16.8	11.8	17.6	17.9	17.7	16.3	10.6
9.5	12.2	10.9	12.5	15.9	9.6	8.6	9.7	10.0	10.3	11.0	8.4
1.05	1.22	0.51	0.90	1.61	1.32	0.96	1.33	1.25	1.13	1.21	0.79
25868	4612721	445956		674238	4732563	324192	3070001	4933955	1017031	5108428	5551688
0.94	0.73	1.42		0.69	1.10	0.33	1.41	1.29	0.70	0.75	0.54
27.11	13.78	1.26		4.34	18.54	24.69	21.04	27.85	17.02	21.04	28.49
6.97	30.07	98.70		23.60	22.59	47.66	23.74	24.81	43.05	42.98	33.84
65.91	56.15	0.04		72.06	58.86	27.65	55.22	47.34	39.93	35.98	37.67
0.94	0.30	0.27		0.47	0.47	0.22	0.34	0.32	0.33	0.25	0.28
29	22	9		63	268	22	45	74	220	107	34
0	21627	95127		0	1548	1	1415	1671	178	1109	231
0.00	0.00	0.30		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.21		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0	93	99	0	0	95	86	97	97	96	95	91
0	0	0	0	0	0	0	0	0	0	0	2
0	7	1	0	0	5	14	3	3	4	5	6
0	68	245	0	0	76	85	87	66	100	53	85
0	28	0	0	0	6	0	0	22	0	42	10
0	4	531	0	0	17	15	13	11	0	5	5
0	64	585	0	0	361	19	282	333	0	158	132
0.00	0.01	-0.08	0.00	0.00	0.11	0.06	0.05	0.06	0.00	0.02	0.01
8.5	2.8	1.8	1.6	2.2	5.5	2.9	6.3	5.0	3.5	2.8	3.8
5	9	12	11	13	7	14	5	8	9	10	9
0	64	87	0	0	74	45	79	78	60	72	67
0	0	0	0	0	0	0	0	0	0	0	2
0	36	13	0	0	26	55	21	22	40	28	32
0	42	164	0	0	57	40	70	53	65	37	58
0	21	0	0	0	5	0	0	17	0	33	6
0	10	127	0	0	5	14	4	4	11	8	10
0	28	5243	0	0	33	45	26	25	24	22	26
0	2710	14452	0	0	3197	382	1772	2874	535	3494	3247
0.00	0.28	-0.26	0.00	0.00	0.96	1.29	0.30	0.51	0.63	0.54	0.18
3.4	2.3	1.4	1.7	2.4	2.9	1.8	3.8	3.0	2.4	2.4	2.0
25	54	74	68	61	43	68	32	36	54	56	52

	Basin number	423	424	425	426	501	502	503	504	505
	Basin name	Warrego River	Paroo River	Darling River	Lower Murray River	Fleurieu Peninsula	Myponga River	Onkaparinga River	Torrens River	Gawler River
CONTEXT	Basin area (km^2)	62937	73965	112823	58286	985	155	915	1130	4582
	Improved pasture (%)	0.57	0.03	0.07	3.95	37.07	41.89	18.35	9.09	7.62
	Cropping (%)	0.09	0.00	0.42	4.35	2.41	3.14	2.80	0.73	33.65
	Horticulture (%)	0.14	0.01	0.06	0.99	0.53	1.86	25.33	13.40	14.69
	Total agricultural land proportion (%)	0.80	0.04	0.55	9.29	40.02	46.89	46.47	23.23	55.97
CLIMATE	Rain (mm/yr)	454	308	296	280	725	742	693	650	465
	Total evaporation (mm/yr)	443	305	286	257	408	420	437	414	366
	Run off (mm/yr)	11	4	11	26	317	332	288	249	106
CARBON	Net primary production (t C/ha/yr)	1.6	0.8	1.0	1.1	3.5	3.3	3.3	2.9	3.0
	Plant carbon (t C/ha)	28.9	13.5	21.5	31.8	128.0	121.1	112.3	96.3	88.3
	Litter + soil carbon (t C/ha)	40.2	25.2	38.7	52.3	132.1	122.7	115.4	100.1	109.3
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.02	0.00	0.06	0.52	1.07	1.23	2.20	1.92	5.81
	Nitrogen fixation (kg N/ha/yr)	5.42	2.56	3.56	10.84	76.47	76.26	35.42	26.06	52.11
	Total nitrogen (kg N/ha)	3377	2026	3118	4243	11510	10640	9912	8525	9197
	Mineral nitrogen (kg N/ha)	44	36	35	39	155	134	87	65	96
	Mineral nitrogen concentration in soil water (mg N/kg W)	43	45	51	63	113	107	78	70	117
	Nitrogen leached (kg N/ha/yr)	3	2	2	4	14	14	9	8	15
	Nitrogen volatilised (kg N/ha/yr)	1.08	0.51	0.68	0.73	2.33	2.20	2.22	1.94	2.01
	Phosphorus from fertiliser (kg P/ha/yr)	0.00	0.00	0.04	0.52	2.54	3.07	1.78	0.83	3.79
	Total phosphorus (kg P/ha)	499	335	430	542	1619	1478	1313	1098	1227
	Dissolved mineral phosphorus (kg P/ha)	8.0	6.5	6.4	6.6	21.0	18.3	14.3	10.8	14.5
	Phosphorus concentration (mg P/kg W)	8.0	8.2	9.3	10.8	15.3	14.7	12.8	11.5	17.7
	Phosphorus leached (kg P/m2/yr)	0.59	0.40	0.45	0.60	1.86	1.91	1.54	1.24	2.23
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	1622326	1046864	3592482	2057263	35434	1482	12425	13590	117291
	Sediment supply (t/ha/yr)	0.36	0.26	0.71	0.85	0.87	0.11	0.18	0.15	0.27
	Proportion from hillslopes (%)	43.16	47.33	8.75	12.58	2.85	45.33	15.58	14.51	11.75
	Proportion from bank erosion (%)	36.84	39.56	81.01	74.96	7.58	30.78	49.64	67.77	43.15
	Proportion from gullies (%)	20.01	13.10	10.24	12.46	89.57	23.89	34.78	17.73	45.10
	Proportion of length with bed deposition > 0.30 m (proportion)	0.17	0.09	0.25	0.41	0.00	0.00	0.00	0.00	0.18
	Sed Ratio (Euro:pre-Euro) (ratio)	16	13	24	14	12	1	4	2	11
	Sediment export to the coast (t/yr)	91	0	169797	564300	13310	641	3820	3223	25422
	Specific sediment export to the coast (t/ha/yr)	0.00	0.00	0.03	0.23	0.33	0.05	0.06	0.04	0.06
	River sediment delivery ratio (export/ supply to streams) (ratio)	0.00	0.00	0.05	0.27	0.38	0.43	0.31	0.24	0.22
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	93	0	97	94	86	63	24	61	61
	Phosphorus from point sources (%)	0	0	0	0	0	0	61	0	0
	Phosphorus - dissolved from diffuse sources (%)	7	0	3	6	14	37	15	39	39
	Phosphorus deposited on floodplain (%)	97	0	262	75	26	5	18	24	44
	Phosphorus deposited in reservoirs (%)	0	0	0	55	0	0	37	18	0
	Phosphorus delivered to estuaries (%)	3	0	22	257	74	95	45	58	56
	Phosphorus - total basin export (t P/yr)	20	0	153	661	9	1	7	4	28
	Phosphorus - export rate (kg P/ha/yr)	0.00	0.00	-0.11	-0.01	0.09	0.08	0.07	0.03	0.06
	Phosphorus load - times pre-European (ratio)	3.7	3.2	2.4	2.7	2.7	0.5	3.9	0.7	2.0
	Phosphorus - dissolved to total (ratio)	7	7	11	8	5	60	39	52	16
	Nitrogen from sediments (%)	71	0	87	71	47	25	20	33	22
	Nitrogen from point sources (%)	0	0	0	0	0	0	28	0	0
	Nitrogen - dissolved from diffuse sources (%)	29	0	13	29	53	75	52	67	78
	Nitrogen deposited on floodplain (%)	69	0	171	42	13	1	4	8	13
	Nitrogen deposited in reservoirs (%)	0	0	0	42	0	0	7	13	0
	Nitrogen - denitrified (%)	14	0	403	37	5	5	11	10	21
	Nitrogen delivered to estuary (%)	16	0	18	1061	82	94	79	69	66
	Nitrogen - total export (t/yr)	606	0	579	14728	74	18	86	57	439
	Nitrogen - export rate (kg/ha/yr)	0.11	0.00	-1.57	-0.05	0.74	1.21	0.92	0.55	0.91
	Nitrogen load - times pre-European (ratio)	1.7	1.6	1.7	2.0	2.2	1.6	2.3	1.2	2.4
	Nitrogen - dissolved to total (ratio)	54	56	59	56	43	86	82	87	69

506 Wakefield River	507 Broughton River	508 Mambray Coast	509 Willochra Creek	510 Lake Torrens	511 Spencer Gulf	512 Eyre Peninsula	513 Kangaroo Island	601 Esperance Coast	602 Albany Coast	603 Denmark River	604 Kent River
1913	16371	5951	6615	26259	10878	3199	4413	20154	19608	2611	2492
12.49	8.44	0.22	3.60	0.00	7.03	7.22	32.88	25.14	28.95	16.04	25.86
53.03	45.11	2.52	11.71	0.04	18.90	14.13	5.13	19.71	20.18	0.44	3.16
9.72	6.29	0.58	1.02	0.00	6.27	0.41	0.40	1.38	2.05	0.58	0.47
75.24	59.84	3.32	16.33	0.04	32.20	21.75	38.40	46.23	51.17	17.06	29.49
399	416	295	318	193	291	483	616	445	481	794	784
331	333	268	293	154	267	328	348	367	369	461	443
68	83	27	26	39	25	156	268	78	112	333	341
2.9	2.6	1.2	1.5	0.3	1.3	2.5	3.5	2.4	2.6	4.3	4.4
80.0	72.7	29.4	42.6	7.3	34.0	74.9	117.0	67.4	81.8	141.6	144.8
110.6	101.8	47.4	70.0	15.1	53.6	91.7	115.8	75.2	82.7	110.7	116.4
7.10	5.55	0.27	1.24	0.00	1.45	2.81	0.27	2.39	4.02	0.21	0.49
71.33	53.88	5.99	15.32	1.03	16.28	29.19	70.63	52.54	60.25	49.59	71.80
9217	8520	3834	5696	1184	4366	7705	9934	6343	7035	9579	10040
106	88	32	47	14	48	81	136	96	119	148	159
148	127	56	77	35	78	89	123	103	115	93	111
19	17	3	5	1	6	9	14	11	13	13	16
1.90	1.70	0.80	1.01	0.20	0.85	1.67	2.33	1.63	1.74	2.89	2.96
5.38	4.90	0.28	1.55	0.00	1.75	2.47	2.04	2.69	4.04	1.65	2.56
1222	1111	488	714	163	602	1062	1442	946	1116	1598	1641
15.1	13.5	5.7	8.3	2.5	8.4	13.4	18.3	13.4	16.9	23.4	23.3
21.2	19.6	10.1	13.7	6.3	14.0	14.9	16.7	14.4	16.3	14.6	16.1
2.70	2.52	0.55	0.95	0.21	0.99	1.56	1.83	1.52	1.79	2.06	2.33
44567	341609	111773	222158	582864	110072	11376	50235	262308	432103	96073	55142
0.32	0.29	0.25	0.37	0.41	0.14	0.07	0.17	0.18	0.26	0.37	0.23
12.80	16.32	48.89	19.71	48.22	46.83	11.74	2.99	6.89	5.70	1.28	1.32
29.76	28.61	9.34	17.75	7.53	27.19	70.03	26.80	18.59	19.60	17.08	17.82
57.44	55.06	41.77	62.55	44.24	25.98	18.23	70.20	74.53	74.70	81.64	80.86
0.15	0.11	0.07	0.48	0.32	0.01	0.03	0.01	0.07	0.22	0.09	0.11
10	9	29	13	13	37	3	63	259	76	36	426
5466	56140	29033	0	1434	21507	3373	17111	40274	80131	31091	14816
0.04	0.05	0.06	0.00	0.00	0.03	0.02	0.06	0.03	0.05	0.12	0.06
0.12	0.16	0.26	0.00	0.00	0.20	0.30	0.34	0.15	0.19	0.32	0.27
61	57	85	81	95	67	35	51	61	64	71	57
0	0	0	0	0	0	0	0	0	0	0	0
39	43	15	19	5	33	65	49	39	36	29	43
54	46	60	75	61	57	31	21	52	49	31	34
0	2	3	0	5	0	0	0	0	0	0	0
46	51	37	25	35	43	69	79	48	51	69	66
9	75	11	16	59	17	6	19	50	85	23	16
0.03	0.05	0.02	0.02	0.02	0.02	0.02	0.04	0.03	0.04	0.08	0.07
2.2	1.8	3.9	4.0	4.5	2.8	1.2	1.5	2.2	2.3	2.4	2.0
10	10	3	3	1	6	27	36	18	15	21	29
20	21	55	47	80	30	9	14	21	22	29	18
0	0	0	0	0	0	0	0	0	0	0	0
80	79	45	53	20	70	91	86	79	78	71	82
16	14	34	39	48	22	4	4	15	14	11	8
0	1	2	0	3	0	0	0	0	0	0	0
24	26	19	31	14	36	20	11	26	22	7	11
60	59	45	30	35	43	76	85	60	64	82	80
165	1236	102	157	310	205	117	366	901	1415	290	267
0.56	0.81	0.16	0.23	0.12	0.21	0.36	0.82	0.45	0.68	1.03	1.14
4.5	3.7	1.9	2.5	3.2	2.3	2.0	1.9	2.0	2.6	1.5	1.9
65	67	47	51	18	54	89	84	82	82	85	90

	Basin number	605	606	607	608	609	610	611	612	613
	Basin name	Frankland River	Shannon River	Warren River	Donnelly River	Blackwood River	Busselton Coast	Preston River	Collie River	Harvey River
CONTEXT	Basin area (km^2)	4657	3297	4404	1731	22565	3061	1134	3713	2002
	Improved pasture (%)	34.84	1.76	10.54	10.93	28.88	34.63	25.18	11.02	29.17
	Cropping (%)	12.98	0.15	1.38	0.14	22.12	0.49	0.67	0.98	1.00
	Horticulture (%)	0.91	0.56	0.58	0.65	3.24	1.03	4.28	0.36	2.83
	Total agricultural land proportion (%)	48.72	2.47	12.50	11.72	54.24	36.14	30.13	12.35	33.01
CLIMATE	Rain (mm/yr)	574	1051	798	1039	547	915	879	802	938
	Total evaporation (mm/yr)	369	487	418	469	345	410	440	416	447
	Run off (mm/yr)	205	565	381	570	202	507	455	390	504
CARBON	Net primary production (t C/ha/yr)	3.4	5.5	4.3	5.6	3.1	2.9	3.9	3.5	3.2
	Plant carbon (t C/ha)	112.5	174.5	138.4	175.6	92.7	79.2	111.2	103.7	81.6
	Litter + soil carbon (t C/ha)	117.0	142.7	132.4	156.2	106.8	77.5	104.0	90.5	75.5
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	1.94	0.49	1.38	0.42	3.62	2.39	5.97	0.52	4.52
	Nitrogen fixation (kg N/ha/yr)	72.86	23.36	39.95	50.99	67.04	55.51	60.55	31.53	54.73
	Total nitrogen (kg N/ha)	9938	12300	11320	13470	8957	6629	8873	7605	6492
	Mineral nitrogen (kg N/ha)	125	130	110	144	108	104	114	92	116
	Mineral nitrogen concentration in soil water (mg N/kg W)	134	86	93	104	132	90	98	76	85
	Nitrogen leached (kg N/ha/yr)	15	16	13	18	15	14	15	12	14
	Nitrogen volatilised (kg N/ha/yr)	2.27	3.65	2.85	3.75	2.04	1.91	2.58	2.37	2.11
	Phosphorus from fertiliser (kg P/ha/yr)	3.58	0.75	2.55	2.07	4.51	5.15	6.90	1.96	5.23
	Total phosphorus (kg P/ha)	1413	1877	1606	1978	1256	1074	1396	1206	1112
	Dissolved mineral phosphorus (kg P/ha)	17.5	23.8	18.8	24.2	15.6	16.7	19.6	15.7	18.3
	Phosphorus concentration (mg P/kg W)	18.3	15.8	15.9	17.4	18.9	14.6	16.9	13.2	13.7
	Phosphorus leached (kg P/m2/yr)	2.02	2.86	2.16	3.01	2.19	2.30	2.59	1.99	2.34
EROSION & SEDIMENT TRANSPORT	Sediment supplied to rivers (t/yr)	191579	12817	109750	16014	801185	71086	72214	104569	56121
	Sediment supply (t/ha/yr)	0.41	0.05	0.25	0.09	0.35	0.31	0.62	0.28	0.38
	Proportion from hillslopes (%)	1.30	0.65	0.87	0.98	2.63	3.05	1.71	3.30	2.94
	Proportion from bank erosion (%)	16.14	38.61	32.14	29.77	27.15	35.35	33.06	38.69	44.66
	Proportion from gullies (%)	82.56	60.74	67.00	69.25	70.22	61.60	65.23	58.01	52.41
	Proportion of length with bed deposition > 0.30 m (proportion)	0.57	0.00	0.08	0.01	0.37	0.05	0.00	0.11	0.11
	Sed Ratio (Euro:pre-Euro) (ratio)	92	170	80	57	247	817	29	>1,000	106
	Sediment export to the coast (t/yr)	26392	5264	27922	5886	97576	24238	24565	21630	17138
	Specific sediment export to the coast (t/ha/yr)	0.06	0.02	0.06	0.03	0.04	0.10	0.21	0.06	0.12
	River sediment delivery ratio (export/ supply to streams) (ratio)	0.14	0.41	0.25	0.37	0.12	0.34	0.34	0.21	0.31
RIVER NUTRIENTS	Phosphorus from fine sediments (%)	72	18	59	28	67	64	75	64	66
	Phosphorus from point sources (%)	0	0	0	0	0	0	0	0	0
	Phosphorus - dissolved from diffuse sources (%)	28	82	41	72	33	36	25	36	34
	Phosphorus deposited on floodplain (%)	61	7	37	12	59	24	27	26	19
	Phosphorus deposited in reservoirs (%)	0	0	0	0	0	0	0	27	5
	Phosphorus delivered to estuaries (%)	39	93	63	88	41	76	73	47	76
	Phosphorus - total basin export (t P/yr)	26	17	29	13	122	21	18	19	18
	Phosphorus - export rate (kg P/ha/yr)	0.05	0.05	0.07	0.07	0.05	0.07	0.15	0.05	0.10
	Phosphorus load - times pre-European (ratio)	3.3	1.2	2.1	1.2	2.4	2.8	3.9	1.6	1.7
	Phosphorus - dissolved to total (ratio)	10	71	25	62	14	26	13	31	45
	Nitrogen from sediments (%)	28	4	21	7	25	26	37	27	28
	Nitrogen from point sources (%)	0	0	0	0	0	0	0	0	0
	Nitrogen - dissolved from diffuse sources (%)	72	96	79	93	75	74	63	73	72
	Nitrogen deposited on floodplain (%)	21	1	10	2	20	9	12	9	7
	Nitrogen deposited in reservoirs (%)	0	0	0	0	0	0	0	8	2
	Nitrogen - denitrified (%)	18	6	11	7	27	5	7	9	5
	Nitrogen delivered to estuary (%)	61	93	78	91	54	86	81	75	86
	Nitrogen - total export (t/yr)	451	311	439	239	1973	305	185	339	234
	Nitrogen - export rate (kg/ha/yr)	0.93	1.02	0.98	1.39	0.87	1.00	1.58	0.91	1.25
	Nitrogen load - times pre-European (ratio)	3.1	1.1	1.6	1.3	3.0	2.3	2.3	1.4	1.6
	Nitrogen - dissolved to total (ratio)	81	98	89	97	84	83	77	90	89

614 Murray River (WA)	615 Avon River	616 Swan Coast	617 Moore-Hill Rivers	618 Yarra Yarra Lakes	619 Ninghan	701 Greenough River	702 Murchison River	703 Wooramel River	704 Gascoyne River	705 Lyndon-Minilya Rivers	706 Ashburton River
9941	117721	8240	24515	42186	20582	25043	91229	41907	75818	52736	75716
23.55	11.32	7.12	20.44	1.67	0.50	8.72	0.46	0.09	0.00	0.00	0.00
10.53	25.99	2.85	18.28	8.55	4.01	22.06	0.65	0.00	0.00	0.00	0.00
4.47	4.47	17.45	6.04	2.46	1.32	8.03	0.99	0.00	0.01	0.01	0.00
38.56	41.77	27.41	44.77	12.67	5.83	38.80	2.10	0.09	0.01	0.01	0.00
706	336	755	494	290	284	369	242	224	251	255	308
396	289	427	355	269	265	307	233	213	246	240	301
310	47	330	139	21	19	61	9	11	5	14	7
3.1	1.5	2.7	2.1	0.8	0.9	1.6	0.3	0.5	0.2	0.3	0.3
86.1	37.3	63.8	42.2	13.8	16.3	28.8	6.0	8.1	3.6	4.6	5.6
89.1	55.0	59.5	49.8	24.1	27.2	42.0	12.1	16.5	8.5	10.6	11.5
1.78	3.90	0.43	3.88	1.39	0.45	4.64	0.14	0.00	0.00	0.00	0.00
51.46	26.50	20.66	39.76	7.49	4.67	28.77	1.74	1.59	0.67	0.88	1.06
7426	4413	4922	4040	1871	2080	3330	920	1196	650	792	909
90	64	64	79	33	31	61	20	20	15	14	18
98	95	60	93	53	49	82	37	39	31	31	31
13	9	9	11	4	3	9	2	2	1	1	2
2.05	1.01	1.79	1.38	0.51	0.58	1.07	0.23	0.31	0.13	0.18	0.21
3.09	2.38	0.45	2.91	0.65	0.22	2.84	0.10	0.00	0.00	0.00	0.00
1095	660	788	693	310	334	555	171	200	120	131	155
13.8	10.0	10.7	11.8	5.6	5.6	9.6	3.6	3.6	2.7	2.5	3.2
14.6	14.8	10.0	14.0	9.0	8.8	13.2	6.6	7.2	5.6	5.5	5.5
1.96	1.33	1.45	1.60	0.61	0.50	1.41	0.29	0.29	0.23	0.23	0.28
459501	1631866	366825	534511	152132	21065	724210	1502684				
0.48	0.38	0.51	0.46	0.25	0.22	0.40	0.30				
2.35	4.39	1.96	2.77	17.31	21.54	6.30	24.60				
22.98	19.82	24.37	15.69	14.15	20.86	17.57	21.05				
74.67	75.79	73.67	81.55	68.54	57.60	76.13	54.34				
0.55	0.60	0.32	0.54	0.10	0.00	0.45	0.14				
598	470	418	32	229	415	91	9				
84754	75636	89746	50819	0	0	116012	21096				
0.09	0.02	0.12	0.04	0.00	0.00	0.06	0.00				
0.18	0.05	0.24	0.10	0.00	0.00	0.16	0.01				
76	73	36	79	90	87	77	92				
0	0	56	0	0	0	0	0				
24	27	8	21	10	13	23	8				
53	86	51	66	63	55	58	95				
0	0	2	0	0	0	0	0				
47	14	77	34	37	45	42	5				
73	78	200	59	14	2	96	19				
0.07	0.01	0.33	0.02	0.00	0.00	0.04	0.00				
2.6	3.0	2.0	3.9	5.7	7.7	5.3	7.2				
24	7	32	9	2	3	4	4				
35	32	25	37	64	61	36	70				
0	0	43	0	0	0	0	0				
65	68	32	63	36	39	64	30				
22	27	20	29	41	35	26	68				
0	0	1	0	0	0	0	0				
13	33	27	23	22	22	23	24				
65	40	52	48	37	43	51	8				
1011	2332	831	777	88	17	1132	169				
1.02	0.19	-4.01	0.31	0.02	0.01	0.44	0.02				
2.1	3.6	1.7	2.6	2.8	2.3	3.1	2.7				
80	77	85	75	53	66	69	51				

	Basin number	707	708	709	710	801	802	803	804	805
	Basin name	Onslow Coast	Fortescue River	Port Hedland Coast	De Grey River	Cape Leveque Coast	Fitzroy River (WA)	Lennard River	Isdell River	Prince Regent River
CONTEXT	Basin area (km^2)	17805	49759	35353	56720	22952	93829	14763	19935	15404
	Improved pasture (%)	0.00	0.00	0.00	0.00	2.69	0.04	0.00	0.01	0.00
	Cropping (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Horticulture (%)	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
	Total agricultural land proportion (%)	0.00	0.00	0.00	0.00	2.70	0.04	0.00	0.01	0.00
CLIMATE	Rain (mm/yr)	362	359	345	356	703	606	802	998	1191
	Total evaporation (mm/yr)	333	346	323	343	544	507	591	673	724
	Run off (mm/yr)	28	13	23	13	159	99	211	325	467
CARBON	Net primary production (t C/ha/yr)	0.4	0.4	0.3	0.3	0.9	0.5	0.9	1.2	1.5
	Plant carbon (t C/ha)	6.4	7.5	4.8	4.5	16.1	9.3	15.6	21.0	26.1
	Litter + soil carbon (t C/ha)	12.2	14.6	10.4	8.4	15.5	11.6	18.9	23.7	28.1
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Nitrogen fixation (kg N/ha/yr)	1.22	1.43	0.91	0.85	3.09	1.78	3.00	4.03	5.04
	Total nitrogen (kg N/ha)	969	1184	828	668	1277	961	1601	2045	2431
	Mineral nitrogen (kg N/ha)	17	21	16	16	28	19	27	28	27
	Mineral nitrogen concentration in soil water (mg N/kg W)	26	30	26	26	23	20	21	22	22
	Nitrogen leached (kg N/ha/yr)	2	2	1	2	3	2	3	4	5
	Nitrogen volatilised (kg N/ha/yr)	0.24	0.29	0.18	0.17	0.62	0.36	0.60	0.81	1.01
	Phosphorus from fertiliser (kg P/ha/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total phosphorus (kg P/ha)	158	195	138	126	256	173	266	314	348
	Dissolved mineral phosphorus (kg P/ha)	3.0	3.9	2.8	2.8	5.0	3.4	4.8	5.1	4.9
	Phosphorus concentration (mg P/kg W)	4.7	5.4	4.6	4.6	4.3	3.6	3.8	4.0	4.0
	Phosphorus leached (kg P/m2/yr)	0.28	0.32	0.26	0.27	0.57	0.38	0.53	0.69	0.85

	Basin number	818	819	820	821	822	823	824	825	826
	Basin name	Mary River (WA)	Wildman River	South Alligator River	East Alligator River	Goomadeer River	Liverpool River	Blyth River	Goyder River	Buckingham River
CONTEXT	Basin area (km^2)	8077	4814	11916	15863	5684	8943	9218	10374	9569
	Improved pasture (%)	0.67	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cropping (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Horticulture (%)	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total agricultural land proportion (%)	0.69	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CLIMATE	Rain (mm/yr)	1341	1396	1363	1379	1296	1237	1186	1145	1315
	Total evaporation (mm/yr)	825	830	807	777	731	716	691	686	737
	Run off (mm/yr)	516	566	555	601	566	521	495	459	578
CARBON	Net primary production (t C/ha/yr)	2.1	2.2	1.8	1.8	1.8	1.5	1.7	1.6	1.9
	Plant carbon (t C/ha)	35.3	37.3	31.6	31.3	30.3	26.3	28.7	28.4	32.8
	Litter + soil carbon (t C/ha)	32.3	36.0	25.4	27.9	23.9	20.8	24.5	24.4	29.2
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Nitrogen fixation (kg N/ha/yr)	6.84	7.24	6.12	6.06	5.87	5.08	5.54	5.48	6.35
	Total nitrogen (kg N/ha)	2787	3132	2183	2413	2048	1791	2108	2100	2535
	Mineral nitrogen (kg N/ha)	35	49	29	41	34	32	38	36	55
	Mineral nitrogen concentration in soil water (mg N/kg W)	24	24	22	23	23	22	23	23	25
	Nitrogen leached (kg N/ha/yr)	5	6	6	6	5	5	5	5	6
	Nitrogen volatilised (kg N/ha/yr)	1.37	1.45	1.22	1.21	1.17	1.02	1.11	1.10	1.27
	Phosphorus from fertiliser (kg P/ha/yr)	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total phosphorus (kg P/ha)	430	515	357	422	370	328	385	372	492
	Dissolved mineral phosphorus (kg P/ha)	6.4	8.9	5.3	7.5	6.3	5.7	7.0	6.5	9.9
	Phosphorus concentration (mg P/kg W)	4.3	4.4	4.0	4.1	4.1	3.9	4.2	4.3	4.5
	Phosphorus leached (kg P/m2/yr)	0.97	1.02	1.00	1.00	0.98	0.92	0.92	0.90	1.04

806 King Edward River	807 Drysdale River	808 Pentecost River	809 Ord River	810 Keep River	811 Victoria River	812 Fitzmaurice River	813 Moyle River	814 Daly River	815 Finniss River	816 Bathurst and Melville Islands	817 Adelaide River
17576	26019	29150	55472	11848	78146	10366	7083	53198	9489	7493	7466
0.08	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.17	2.28	0.00	0.45
0.17	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.00
0.13	0.02	0.00	0.01	0.04	0.00	0.00	0.00	0.00	5.50	0.00	6.78
0.38	0.03	0.00	0.01	0.06	0.00	0.00	0.00	0.17	7.81	0.00	7.23
1218	1010	768	651	931	732	1154	1382	1066	1595	1705	1403
764	699	603	550	651	590	736	782	714	874	856	844
455	311	165	102	280	142	418	599	353	721	850	559
1.5	1.1	0.6	0.6	0.9	0.8	1.5	2.0	1.6	2.2	2.7	2.2
26.3	18.3	10.7	11.1	16.4	14.4	26.4	35.1	26.8	38.3	46.5	37.1
29.1	16.4	9.6	13.8	16.7	17.8	23.2	34.2	26.5	37.2	46.2	37.3
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01
5.18	3.53	2.05	2.13	3.15	2.76	5.10	6.80	5.17	7.45	9.05	7.20
2537	1406	807	1158	1431	1516	1988	2959	2267	3234	4043	3232
30	24	18	21	24	24	30	37	30	48	82	39
22	20	19	20	19	21	22	24	22	24	27	24
5	4	3	2	3	3	5	5	4	6	7	5
1.02	0.71	0.41	0.43	0.63	0.55	1.02	1.36	1.03	1.49	1.81	1.44
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
363	249	164	201	245	245	336	450	353	515	738	476
5.4	4.4	3.3	3.8	4.3	4.3	5.5	6.8	5.4	8.6	15.0	7.1
3.9	3.6	3.3	3.6	3.4	3.7	3.9	4.4	4.1	4.3	4.9	4.4
0.83	0.67	0.48	0.41	0.55	0.47	0.82	0.98	0.75	1.14	1.33	1.00

901 Koolatong River	902 Walker River	903 Roper River	904 Towns River	905 Limmen Bight River	906 Rosie River	907 McArthur River	908 Robinson River	909 Calvert River	910 Settlement Creek	911 Mornington Island	912 Nicholson River
7910	9715	79630	5433	15939	5039	20010	11371	10016	17319	1236	51625
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	5.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00
0.00	0.00	5.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00
1177	970	824	678	652	753	656	723	721	793	1018	518
723	656	600	532	533	582	551	585	595	633	637	470
454	314	225	146	119	171	106	138	126	160	381	48
2.0	1.4	1.0	0.8	0.7	0.9	0.7	0.9	1.1	1.1	1.2	0.5
34.9	25.0	18.1	14.0	12.4	16.2	12.9	16.2	18.7	18.8	20.8	9.4
28.7	19.5	17.9	13.3	12.2	13.6	12.6	14.5	16.6	19.9	23.7	13.4
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.75	4.81	3.48	2.69	2.37	3.11	2.47	3.11	3.60	3.61	4.01	1.80
2482	1662	1513	1107	1011	1133	1040	1206	1378	1685	2051	1114
51	32	25	23	20	22	20	21	21	26	33	21
26	23	21	21	21	21	21	22	23	23	22	23
6	4	3	3	2	3	3	3	3	3	4	2
1.35	0.96	0.70	0.54	0.47	0.62	0.49	0.62	0.72	0.72	0.80	0.36
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
484	321	260	218	191	221	196	223	243	276	333	194
9.4	5.8	4.5	4.2	3.6	4.0	3.6	3.9	3.9	4.6	5.9	3.8
4.7	4.2	3.8	3.8	3.7	3.8	3.7	3.9	4.2	4.1	3.9	4.2
1.02	0.77	0.56	0.48	0.45	0.55	0.46	0.52	0.57	0.55	0.64	0.36

	Basin number	913	914	915	916	917	918	919	920	921
	Basin name	Leichhardt River	Morning Inlet	Flinders River	Norman River	Gilbert River	Staaten River	Mitchell River (WA)	Coleman River	Holroyd River
CONTEXT	Basin area (km^2)	33307	3613	109728	50022	46292	25824	71529	12900	10217
	Improved pasture (%)	0.00	0.00	0.16	0.17	3.06	0.90	2.44	0.00	0.00
	Cropping (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.01	0.00
	Horticulture (%)	0.00	0.00	0.00	0.00	0.01	0.00	0.12	0.05	16.22
	Total agricultural land proportion (%)	0.00	0.00	0.17	0.17	3.07	0.90	2.62	0.06	16.22
CLIMATE	Rain (mm/yr)	509	659	468	637	729	862	942	1239	1335
	Total evaporation (mm/yr)	470	541	438	539	583	627	669	719	731
	Run off (mm/yr)	39	118	30	99	145	235	273	521	604
CARBON	Net primary production (t C/ha/yr)	0.6	0.6	0.6	0.8	1.2	0.9	1.5	1.4	1.8
	Plant carbon (t C/ha)	10.5	10.7	10.6	13.9	21.6	14.8	25.4	24.9	30.8
	Litter + soil carbon (t C/ha)	15.9	18.0	18.7	15.7	25.7	17.0	24.4	23.9	29.1
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.01
	Nitrogen fixation (kg N/ha/yr)	2.00	2.06	2.03	2.66	4.15	2.84	4.93	4.82	5.96
	Total nitrogen (kg N/ha)	1320	1542	1581	1305	2187	1444	2086	2057	2506
	Mineral nitrogen (kg N/ha)	21	22	26	26	30	23	33	35	43
	Mineral nitrogen concentration in soil water (mg N/kg W)	25	20	27	23	26	21	25	22	24
	Nitrogen leached (kg N/ha/yr)	2	2	2	3	3	3	4	5	5
	Nitrogen volatilised (kg N/ha/yr)	0.40	0.41	0.41	0.53	0.83	0.57	0.98	0.96	1.19
	Phosphorus from fertiliser (kg P/ha/yr)	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
	Total phosphorus (kg P/ha)	210	223	244	240	336	234	353	354	437
	Dissolved mineral phosphorus (kg P/ha)	3.8	3.9	4.6	4.6	5.5	4.1	6.1	6.3	7.9
	Phosphorus concentration (mg P/kg W)	4.5	3.6	4.8	4.2	4.8	3.8	4.6	4.0	4.3
	Phosphorus leached (kg P/m2/yr)	0.38	0.35	0.35	0.47	0.58	0.53	0.74	0.82	0.97

	Basin number	005	006	007	011	012	021	022	023	024
	Basin name	Finke River	Todd River	Hay River	Bulloo River	Lake Lake Bancannia	Gairdner	Nullarbor	Warburton	Salt Lake
CONTEXT	Basin area (km^2)	100085	59653	99804	75528	23292	197878	190737	371640	494827
	Improved pasture (%)	0.00	0.00	0.00	0.04	0.00	1.39	0.00	0.00	0.47
	Cropping (%)	0.00	0.00	0.00	0.01	0.00	4.35	0.00	0.00	0.33
	Horticulture (%)	0.00	0.31	0.00	0.00	0.00	0.21	0.00	0.00	0.04
	Total agricultural land proportion (%)	0.00	0.31	0.00	0.05	0.00	5.95	0.00	0.00	0.84
CLIMATE	Rain (mm/yr)	187	190	160	284	204	217	206	189	252
	Total evaporation (mm/yr)	186	190	159	281	202	196	201	188	245
	Run off (mm/yr)	1	0	1	3	2	21	5	1	7
CARBON	Net primary production (t C/ha/yr)	0.3	0.3	0.2	0.5	0.3	0.6	0.4	0.3	0.6
	Plant carbon (t C/ha)	5.2	5.7	3.2	9.0	5.3	13.4	8.7	5.7	13.3
	Litter + soil carbon (t C/ha)	12.3	12.1	7.4	17.7	14.1	24.3	17.5	12.0	22.3
LANDSCAPE NUTRIENTS	Nitrogen from fertiliser (kg N/ha/yr)	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.00	0.04
	Nitrogen fixation (kg N/ha/yr)	0.98	1.08	0.60	1.70	0.97	4.23	1.23	1.07	2.79
	Total nitrogen (kg N/ha)	895	831	497	1418	1101	1897	1363	856	1748
	Mineral nitrogen (kg N/ha)	15	13	9	28	23	21	20	18	25
	Mineral nitrogen concentration in soil water (mg N/kg W)	41	41	35	41	44	48	45	44	44
	Nitrogen leached (kg N/ha/yr)	1	1	1	2	1	2	2	2	2
	Nitrogen volatilised (kg N/ha/yr)	0.20	0.22	0.12	0.34	0.19	0.37	0.25	0.21	0.41
	Phosphorus from fertiliser (kg P/ha/yr)	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.05
	Total phosphorus (kg P/ha)	147	141	90	245	191	264	207	160	273
	Dissolved mineral phosphorus (kg P/ha)	2.7	2.4	1.7	5.1	4.1	3.8	3.5	3.2	4.6
	Phosphorus concentration (mg P/kg W)	7.4	7.5	6.2	7.4	8.0	8.6	8.2	8.1	7.9
	Phosphorus leached (kg P/m2/yr)	0.24	0.27	0.19	0.34	0.26	0.41	0.29	0.28	0.36

922	923	924	925	926	927	928	929	001	002	003	004
Archer River	Watson River	Embley River	Wenlock River	Ducie River	Jardine River	Torres Strait Islands	Groote Eylandt	Georgina River	Diamantina River	Coopers Creek	Lake Frome
13858	4682	4688	7468	6809	3287	566	2367	247861	157418	297570	201672
0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.66	0.04
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20
15.61	47.72	13.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
15.69	47.72	13.90	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.67	0.25
1432	1715	1803	1569	1595	1672	1775	1060	239	230	301	162
753	773	786	792	773	796	823	713	236	224	296	147
679	942	1017	777	822	876	952	347	3	6	5	15
2.3	2.2	2.1	2.5	2.5	3.5	1.9	1.8	0.2	0.1	0.5	0.2
39.6	37.3	36.5	43.3	42.2	60.0	32.0	31.2	3.7	2.2	8.4	3.7
37.5	35.7	34.1	39.4	37.4	48.1	20.9	22.2	9.1	6.5	17.0	8.6
0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
7.67	7.22	7.08	8.42	8.20	11.68	6.24	6.03	0.69	0.43	1.60	0.70
3247	3085	2945	3420	3243	4173	1777	1898	695	522	1388	665
54	49	48	65	66	92	29	34	15	14	23	12
27	25	24	28	28	34	23	25	31	30	36	34
6	7	7	7	7	10	8	5	1	1	2	1
1.53	1.44	1.42	1.68	1.64	2.34	1.25	1.21	0.14	0.09	0.32	0.10
0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
555	514	496	620	610	834	329	361	125	100	217	106
9.9	8.9	8.7	11.8	11.9	16.7	5.2	6.1	2.7	2.5	4.2	2.0
4.9	4.5	4.4	5.1	5.0	6.2	4.2	4.5	5.5	5.2	6.5	5.9
1.18	1.24	1.28	1.31	1.36	1.85	1.46	0.92	0.21	0.19	0.31	0.17

025	026	027	028	029
Sandy Desert	Mackay	Burt	Wiso	Barkly
404341	403000	38836	229294	124011
0.04	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.04	0.00	0.00	0.01	0.01
314	283	266	398	357
301	275	265	374	344
13	8	1	25	13
0.2	0.3	0.5	0.5	0.3
3.9	5.8	9.4	8.2	6.0
5.9	9.6	16.5	11.2	11.7
0.00	0.00	0.00	0.00	0.00
0.74	1.10	1.78	1.55	1.15
438	706	1225	868	940
14	17	20	18	19
25	31	39	26	25
1	2	2	2	1
0.15	0.22	0.35	0.31	0.23
0.00	0.00	0.00	0.00	0.00
104	143	208	164	164
2.5	3.0	3.7	3.2	3.4
4.5	5.7	7.1	4.7	4.5
0.26	0.29	0.35	0.33	0.26

GLOSSARY

Acidic soil

Soil with a pH < 7.0 in a soil–water suspension.

Agricultural lime

A soil conditioner containing calcium carbonate (commonly from limestone) used to neutralise soil acidity and in some soils to provide calcium.

Algal blooms

A proliferation of microscopic algae in rivers and lakes, stimulated by input of nutrients such as phosphorus and nitrogen.

Alkaline soil

A soil with a pH > 7.0.

Aquifer

A rock layer that holds water

Alluvial

Sediments deposited from flowing water into floodplains.

Alluvial fan

Material deposited by a stream where it emerges from the constriction of a valley to a plain.

Arid zone

Those areas in Australia that receive less than 250 or 350 mm of rainfall each year in the south and north respectively.

Annual cropping

A system where one crop is grown each year. Refer also to *double cropping*.

Biomass

A mass (weight) of plant material.

Broadacre farms

Commercial farms over a large area. Produce includes crops, wool, beef and sheep meat. Farming is usually under dryland conditions.

Buffering capacity

The ability of the soil to resist changed conditions.

C3 & C4 plants

C3 plants comprise more than 95 percent of the plant species on earth. (Trees, for example, are also C3 plants.).

C4 plants, such as the common marsh grasses and other herbaceous plants, are abundant in arid, hot environments. They include such crop plants as sugar cane, corn, and soybeans, and are the second most prevalent photosynthetic type.

The C3 and C4 refer to how these classes of plants assimilate carbon dioxide into their systems. During the first steps in CO2 assimilation, C3 plants form a pair of three carbon-atom molecules. C4 plants, on the other hand, initially form four carbon-atom molecules.

The important difference between C3 and C4 species for rising carbon dioxide levels is that photosynthesis in C4 species is saturated with carbon dioxide at present levels, while C3 species continue to increase for photosynthesis as carbon dioxide rises.

Catchment

An area of land where run-off from rainfall goes into the one river system.

Clay

Soil particles < 0.002 mm in diameter.

Climate variability

The natural year to year, and season to season variation of the climate system.

Codes of practice

Sets of agreed guidelines adopted by rural industries and the agricultural service sector to minimise the impacts of farming operations on the environment.

Conservation farming

A farming system that creates a suitable environment for growing crops and pasture with an emphasis on conserving soil and water resources, and consistent with sound economic practices.

Crop management

A series of management options (e.g. choice of crops within a rotation, variety of plant, length and type of fallow, time of sowing, residue management, pesticide, soil conditioner and fertiliser practices, and type and number of tillage operations).

Denitrification

The chemical or microbial conversion of soil nitrate or nitrite to gaseous nitrogen or an oxide of nitrogen.

Deposition

Occurs when the sediment load of a given particle type exceeds the energy available to move it. This often results from a reduced gradient, flow velocity or discharge or an increase in the hydraulic resistance the flow induced by vegetation. Deposition results in sedimentation.

Detachment

Detachment of soil particles occurs when the erosive forces of raindrop impact or of flowing water exceed the soil's resistance to erosion. It is influenced by the forces of impact and flowing water, how likely the soil is to erode, the presence of plants or other material that reduces the magnitude of eroding forces, and management of the soil that makes it less susceptible to erosion. Detachment can also be caused by soil organisms such as ants or burrowing animals.

Digital elevation model (DEM)

A geographic grid of an area where the contents of each grid square represent the height of the landscape in that cell.

Direct sowing

Any system of sowing, or crop or pasture establishment where seed is placed into soil that has not been ploughed. Sometimes termed zero tillage.

Double cropping

Growing a summer and a winter crop on the same land within a 12-month period.

Deep drainage

Movement of soil water and solutes through the soil and beyond the root zone.

Dryland cropping

Cropping without irrigation.

Dryland salinity

Where water balance has been altered due to changing land use (e.g. clearing of native vegetation for broadacre farming or grazing), excess water entering the watertable mobilises salt which then rises to the land surface. Movement of water drives salinisation processes and may move the stored salt towards the soil surface or into surface water bodies.

Effective rainfall

Rainfall that is available for plant growth.

Erodibility

How likely the soil is to erode.

Essential chemical elements

Elements required by plants and animals to complete their life cycles.

Estuary

An inlet or river mouth that is influenced by tides from the sea and fresh water from land. The area where fresh and salt waters mix.

Eutrophication

Process whereby waters become enriched with nutrients (mainly phosphorus and nitrogen), stimulating growth of aquatic flora and/or fauna.

Erosion

The continuing process of landscape development as a smoothing or levelling of the earth's surface by removal of weathered material.

Natural erosion is due only to the forces of nature; accelerated erosion occurs as a result of human activities. In each case the same processes operate and the distinction is often only a matter of degree and rate.

Erosivity

The potential ability of an agent to cause soil erosion.

Fallow

The practice of maintaining land free of plant growth. Land is left either in a cultivated or herbicide-treated state for a period before sowing a crop or between successive crops. It is mainly carried out to conserve soil water and mineralise soil organic nitrogen reserves. The period of fallow can vary from between on to three months (short fallow) to 14 months (long fallow).

Farm-gate nutrient balance

The difference between the total amount of a nutrient applied to land as fertiliser, soil conditioners and legume nitrogen fixation and the total amount of that nutrient exported in harvested farm products.

Fertiliser requirement

The extra amount of a particular nutrient needed to increase plant growth to a designated level.

Foot slope

The lower part of a slope above the gentler gradient of a valley floor or plain.

Flux

The rate at which energy, water, nutrients and radiation flow across an area.

Geo-morphological processes

Processes that make up the physical and chemical interactions between the Earth's surface and natural forces (e.g. gravity, ice, water, wind, waves) that produce landforms.

Groundwater

Water occurring below the ground surface

Gully density

The linear extent of a gully, measured as kilometres of gully per square kilometre of land.

Gully erosion

Removal of soil by running water which results in the formation of deep channels (gullies) that tend to form in upland areas, have steep sides , and usually transport surface run-off to relatively small drainage areas. Gullies are at least 50 cm deep. They erode unchannelled valleys and dips, and eventually become vegetated and infill, distinguishing them from depressions that have permanent streams.

Gypsum

The common name for calcium sulfate, used to supply calcium and sulfur to plants and to ameliorate sodic soils.

Headcuts

A sharp ephemeral waterfall cut into soil at the head of a gully or incised stream. Over time the headcut migrates upslope by the scouring and toppling of the soil.

Hillslope

All the land surface above a stream or channel edge.

Incised streams

Permanent streams which have deepened and widened by several metres as a result of plants being removed or increased forces of flow. These streams have high, bare vertical banks with headcuts incised into floodplains. They resemble large gullies.

Infiltration

Passage of water through the soil surface and into the soil.

Intensive agricultural land use(s)

Areas described as intensive agriculture generally include Horticulture; Semi-intensive (irrigated and non-irrigated) – sugar, cotton, rice, potatoes; Broadacre crops (irrigated and non-irrigated) – cereals, wheat, oilseeds, pulses, hay; Pastures (irrigated and non-irrigated) – livestock, dairy production from improved pastures.

Leaching

Movement of materials in solution from the soil.

Ley-farming

A farm rotation that specifically includes a legume-based pasture to improve soil fertility as well as to provide grazing for livestock. This system of land use is confined mainly to southern Australia.

Lime requirement

The amount of lime required to change the soil to a specified state of pH or soluble aluminium content.

Macro-nutrient

The essential plant nutrients nitrogen, phosphorus, potassium, sulfur, calcium and magnesium.

Maintenance application

Applications of fertilisers in amounts and intervals to maintain available soil nutrients at levels necessary to produce desired yields.

Mineralisation

The conversion of an element from an organic form to an inorganic state as a result of microbial activity.

Monitoring

Routine counting, testing or measuring environmental factors to estimate their status or condition

Net primary productivity

The difference between the levels of plant photosynthesis and respiration, that determine how much plant is produced—typically measured as a mass per unit area.

Nitrification

Oxidation of ammonium to nitrate or nitrite.

Nitrogen fixation

Conversion of gaseous nitrogen into more complex organic molecules that can be used by plants and other organisms. The process is usually carried out by soil micro-organisms in association with leguminous plants.

Nutrient availability

The ease with which plants can absorb a particular nutrient from the soil. Different fractions within the total nutrient pool will have different availabilities, depending on solubility, rates of dissolution and diffusion to plant roots.

Off-site impacts

Consequences of an action or decision that occurs beyond the area under consideration.

Perennial plant

Plants that live more than one year.

Photosynthesis

The process that plants use to convert carbon dioxide and water into plant organic matter. Photosynthesis is powered by energy from the sun.

Plant nutrient

An element absorbed by plants that is necessary for completion of the life cycle.

Rangelands

Areas of native grasslands, shrublands, woodlands, and tropical savanna woodlands that cover a large proportion (75%) of the arid and semi-arid regions of (outback) Australia.

Recharge

Rainfall that moves through the soil, beyond the roots of plants, to replenish the aquifer.

Regolith

The unconsolidated covering of weathered rock and soil on the earth's surface. It consists of loose earth materials above solid rock.

River basins containing intensive agriculture

The catchments of the east coast of Australia from Cape York to the Eyre Peninsula, of Tasmania, of south-west Western Australia, and of the Ord Basin. These river basins include forests and rangelands as well as intensive agriculture.

Reduced tillage

Any procedure for preparing land for sowing, where herbicides partially replace cultivation. Also known as minimum tillage.

Residue

Portion of plant or crop left in the paddock after harvest. Often referred to as crop stubble or pasture residue. Residues can be retained, incorporated into the soil or burnt.

Revised Universal Soil Loss Equation (RUSLE)

The RUSLE calculates mean annual erosion (tonnes/ha/yr) as a product of rainfall erosivity, soil erodibility, hillslope length, hillslope gradient, ground cover and land use. However, because the slope steepness factor of the original equation (the USLE) overestimates erosion from slopes steeper than 9%, the RUSLE applies a different slope steepness equation to determine the hillslope gradient factor.

Rill erosion

Erosion where concentrated wash causes the formation of tiny channels or rills, a few centimetres to 50 cm deep, which usually carry water only during storms and which can be removed by tilling.

Run-off

The proportion of precipitation that is not immediately absorbed by the soil and thus flows across the surface.

Salinisation

The process whereby soluble salts accumulate in the soil.

Salinity

The total amount of water-soluble salts present in a soil horizon.

Sand

Soil particles between 0.005 and 2.0 mm in diameter.

Silt

Soil particles between 0.05 and 0.002 mm in diameter.

Siltation

Deposition of sediments from water in channels, reservoirs and harbours

Sediment

Solid material (predominantly small particles of sand, silt, rock and vegetable material) that have been transported by water and deposited or settled out of suspension.

Sediment delivery ratio (SDR)

SDR is measured as the ratio of gross erosion upstream to the sediment yield at a particular point and measures efficiency of transport and intensity of deposition upstream. Gross erosion is rarely measured and typically sediment yield of hillslope plots is the measure of erosion.

Sediment transport

The entrainment and movement of sediment from its original location after it has been detached from the soil. It is a function of the energy of the flowing water and size of particles; deep, fast flows have a greater capacity to transport sediment, fine particles are moved more easily than larger or heavier ones.

Sediment yield

The amount of material transported past a given point (usually a measuring device in a stream or a point on a hill slope). It is the net result of erosion, transport and deposition upstream or upslope.

Semi-arid zone

Lands where rainfall is too low and unreliable for crops to be grown with certainty.

Sheetwash or surface wash erosion

The removal of a relatively uniform layer of soil by raindrop splash and/or by diffuse surface run-off during intense storms. It occurs on land where soil is not protected by a surface cover such as vegetation.

Soil acidification

A gradual increase in the acidity of a soil as a consequence of a variety of natural processes and management actions.

Sodic soil

Soils containing a high proportion of sodium. Sodic soils cause poor physical conditions for plant growth. They are typically considered unstable and, as a consequence, have high erodibility and often present problems for soil conservation strategies.

Soil creep

Imperceptibly slow but continuous movement or displacement of soil or subsoil, evidenced by leaning trees and fences, and bowed walls.

Soil fertility

The ability of a soil to supply the nutrients essential to plant growth.

Soil organic matter

The organic fraction of the soil. Organic matter does not include undecayed plant and animal residues.

Soil pH

A measure of soil acidity or alkalinity. It is expressed as the negative logarithm of the hydrogen ion activity of a soil—typically between 3.5 and 8.5.

Soil test

A chemical, physical or biological procedure that estimates a property of the soil to gauge its suitablility to support plant growth.

Stocking rate

The number of animals over a specified land area.

Stream bank erosion

The removal of soil from stream banks by the direct action of water in the channel. It typically occurs under high flow conditions by scour and mass failure processes, and particularly by undercutting of the toe of the bank.

Stream link

The division of a river into lengths of stream between tributary junctions.

Surface run-off

Most soil eroded by water is transported downslope by *surface run-off*.

Terrace

A flat or gently inclined land surface bounded by a steeper ascending slope on its inner margin and a steeper descending slope on its outer margin.

Tillage

Mechanical disturbance of the soil using various implements to alter soil structure. Tillage is usually done to create a seed bed, control weeds or to improve water infiltration into soil.

Turbidity

How clear water is. Water clarity can be affected by suspended and colloidal particles, such as clay and organics.

Universal Soil Loss Equation (USLE)

The USLE (Y) calculates mean annual erosion (tonnes/ha/yr) as a product of: rainfall erosivity factor (R), soil erodibility factor (K), hill slope length factor (L), hill slope gradient factor (S), ground cover factor (C) and land use practice factor (P):

$Y = R*K*L*S*C*P$

The precise form of each factor is based on soil loss measurements on hill slope plots, mainly in the USA. Refer to Revised Universal Soil Loss Equation (RUSLE).

Water-repellent soil

Soils, which when dry, do not allow drops of water to spread spontaneously over surfaces and into soil pores.

Waterlogging

The saturation of soil with water; often associated with insufficient oxygen for good plant growth.

Watertable

A surface defined by the level to which water rises in an open well or piezometer.

Woodland

An area with scattered trees, where the portion of land surface covered by the crowns of trees is more than 30% (open woodland), but less than 60% (forest).

Yield

The amount of specified substance produced (e.g.. grain, straw, meat, total dry matter) per unit area.

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NATIONAL LAND AND WATER RESOURCES AUDIT

Who is the Audit responsible to?

The Minister for Agriculture, Fisheries and Forestry – Australia has overall responsibility for the Audit as a program of the Natural Heritage Trust. The Audit reports through the Minister for Agriculture, Fisheries and Forestry to the Natural Heritage Board which also includes the Minister for the Environment and Heritage.

How is the Audit managed?

An Advisory Council manages the implementation of the Audit. Dr Roy Green, with a background in research, science policy and management chairs the Advisory Council. Members of the Advisory Council and the organisations they represent in October 2001 are: Warwick Watkins (L&WA), Geoff Gorrie (AFFA), Stephen Hunter (EA), John Radcliffe (CSIRO), Peter Sutherland (SCARM), Jon Womersley (SCC), Roger Wickes (SCARM) and Colin Creighton (Audit).

What is the role of the Audit Management Unit?

The Audit Management Unit's role has evolved over its five-year life. Phases of activity include:

Phase 1. Strategic planning and work plan formulation—specifying (in partnership with Commonwealth, States and Territories, industry and community) the activities and outputs of the Audit—completed in 1998–99.

Phase 2. Project management—letting contracts, negotiating partnerships and then managing all the component projects and consultancies that will deliver Audit outputs—a major component of Unit activities from 1998–99 onwards.

Phase 3. Reporting—combining outputs from projects in each theme to detail Audit findings and formulate recommendations—an increasingly important task in 2000–2001 and the early part of 2001–02.

Phase 4. Integration and implementation—combining theme outputs in a final report, working towards the implementation of recommendations across government, industry and community, and the application of information products as tools to improve natural resource management—the major focus for 2001–2002.

Phase 5. Developing long term arrangements for continuing Audit-type activities—developing and advocating a strategic approach for the continuation of Audit-type activities—complete in 2001–2002.

The Audit Management Unit has been maintained over the Audit's period of operations as an eight-person multidisciplinary team. This team as at October 2001 comprises Colin Creighton, Warwick McDonald, Stewart Noble, Maria Cofinas, Jim Tait, Rochelle Lawson, Sylvia Graham and Drusilla Patkin.

How are Audit activities undertaken?

As work plans were agreed by clients and approved by the Advisory Council, component projects in these work plans were contracted out. Contracting involves negotiation by the Audit to develop partnerships with key clients or a competitive tender process.

Facts and figures

• Total Audit worth, including all partnerships	in excess of $52 m
• Audit allocation from Natural Heritage Trust	$34.19 m
• % funds allocated to contracts	~ 92%
• Total number of contracts	149

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National Land & Water Resources Audit

A program of the Natural Heritage Trust

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