MEAT & LIVESTOCK AUSTRALIA

Western Victoria Research Site SGS Harvest Year

Nutrient Theme

Project number SGS.114B
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Highlights

The Harvest Year enabled the following :

- Soil coring undertaken at the end of the National Experiment in spring 2001 allowed the use of soil profile mineral N as a surrogate for N leaching measurements
- A rule of thumb was developed, which indicates that to replace the N removed by product only between 10 and 20% legume is necessary. Higher legume percentages than this lead to a build-up of N in the soil, and an increased risk of N leaching.
- Cross-site analysis of runoff water quality data showed that across central and southern Sites (Carcoar, Maindample, Ruffy, and Vasey) higher soil fertility was associated with higher P concentrations in runoff water
- At the northern Sites (Barraba, Manilla and Nundle), there was no relationship between soil fertility and the P concentration in surface runoff. There was, however, a strong relationship between total P and suspended sediment concentration. Both these parameters were strongly related to quantity of runoff and the proportion of bare ground. Heavily stocked continuously grazed treatments were associated with a high proportion of bare ground, high surface runoff, and high P load.
- High spatial variation in the generation of surface runoff was demonstrated at all Eastern States Sites except Maindample. This means that there is an opportunity to minimise water quality problems associated with grazing management by identifying those areas that produce the most runoff, and managing them as low-phosphorus systems.

Highlights from the Theme prior to the Harvest Year were :

- A minimum protocol was developed which obtained a useful and common set of data across sites and was not too demanding on Site resources
- Results from the National Sites highlighted how the more intensive grazing systems based on pasture improvement, higher fertility and higher stocking rates have few environmental problems on some parts of the landscape, but not on others. In many cases the most financially rewarding pasture system also had similar or fewer environmental problems (recharge to groundwater, acidification, erosion risk, loss of nutrients to waterways). There were, however, notable exceptions such as on gradational soils and steep hills.
- Quantities of P and N in runoff waters from sheep pastures were much lower than anticipated at the start of the SGS program, and amount to less than $0.50/ha.year of P fertiliser equivalent
- In some environments a high proportion of surface runoff exceeded the healthy stream standard of 0.05 mg P/litre; how much of this reaches the stream is unclear.
- New research leads have been found for how to capture the benefit of fertiliser application while minimising P loss in waterways, i.e. by intensifying production on areas less likely to contribute to surface runoff.
- N losses on high, medium and low intensity systems were similar, and thus high input systems are no less environmentally acceptable than lower input ones.
- Very little N is lost in surface runoff but substantial amounts can be lost in subsurface flow and deep drainage; the concentration of N in surface runoff can exceed the World Health Organisation drinking water level of 10 mg N/litre, and well-exceed the stream health figure of 0.5 mg N/litre). Whether this ends up in waterways is unclear but it raises serious political issues about current agricultural systems, particularly those based on annual pastures.
- Nitrogen application has been found to increase the growth and improve the quality of a kikuyu-subclover pasture when applied prior to out-of-season summer rainfall.
- Nitrogen application to a phalaris-subclover pasture during winter produced no extra pasture growth during the target period, and caused reduced gross margins. There is therefore limited scope to increase pasture production on phalaris-sublclover pastures where there have been high legume percentages over a sustained period.

Background to the Theme and key questions

The Theme was initially set up to develop a minimum protocol for nutrient sampling and analysis. As SGS developed, the Theme's plans addressed the following objective:

For a range of the major climatic regions of the High Rainfall Zone where temperate perennial pastures are an important land use, to quantify the positive and negative effects of N and applied P both on and off site on

- pasture and animal productivity;
- soil acidification; and
- P and N concentrations in runoff waters

Overview of progress against the contract objectives

SGS (to June 2001): The Theme provided leadership and co-ordination of:

- Research into the dynamics of nutrients in intensive pasture systems
- forage mineral nutrient analyses
- soil analyses for a standard fertility description of two treatments at each Site (low and high fertility
- soil analyses for pH buffering capacity.

In addition, the Theme has provided a focus for issues concerning intensive *vs* extensive pastures. The Theme leader is also involved in the Triple P research program, funded by Wool Innovations Limited and the NRE Wool Program, and a Dairy Nitrogen project funded by DRDC, ARC and the NRE Dairy Program. His co-involvement has enabled substantial synergies that have allowed the SGS program rapid access to the latest findings from these other programs.

Harvest Year: The Theme provided leadership and co-ordination of:

- soil coring, conducted at all National Experiment Sites to determine mineral N store, exchangeable Al, and total P
- Cross-site relationships between soil fertility and P concentrations in surface runoff
- Long-term simulations of contrasting HRZ grazing management and pasture scenarios using the SGS Model, which showed large reductions in N leaching through kikuyu
- Preparation of the Theme paper for the special edition of the AJEA.

Tools, Rules of Thumb, and Guidelines

1. N export in product for a ewe-lamb enterprise is approximately 1 kg of N per DSE
2. N fixation is approximately 28 kg N per tonne of legume growth
3. Combining these rules of thumb, the long-term safe legume percentage can be calculated from stocking rate (*S*, DSE/ha) and pasture growth (*G*, tonnes/ha.year) as 100 *S*/(28 *G*), and ranges between 10 and 20%. Higher legume percentages than this are likely to lead to N build-up in the soil, and an increased soil acidification risk. Lower percentages would lead to a run-down in grass vigour through N deficiency.

Findings Hunches and Uncertainties

Findings

Environmental aspects

1. The concentration of P in surface runoff was related to soil fertility at the southern Sites (Carcoar, Maindample, Ruffy and Vasey), indicating that greater use of P fertiliser would increase P movement

into waterways. At northern Sites (Barraba, Manilla and Nundle) runoff P concentration was not related to fertility, but instead related to suspended sediment concentration. **(Multi-site analysis)**

2. There was no relationship between runoff N concentration and fertility. **(Multi-site analysis)**

3. Across all Sites, both P and N concentrations in surface and sub-surface runoff were well above guidelines for healthy streams. The guidelines refer to periods of low flow, whereas surface runoff events contribute to high streamflow. **(Multi-site analysis)**

4. Across most Sites, there was considerable spatial variation in surface runoff generation. Furthermore, only a small proportion of streamflow was generated from the portion of the landscape represented by the National Experiment. The SGS Sites represented the portion of the landscape most likely to be improved under commercial conditions. Areas contributing disproportionately to runoff generation are likely to be riparian zones and areas of convergent topography. It is recommended overall production be increased by focussing intensification on the suitable land units and retiring from production the parts of the landscape that produce the greatest proportion of surface flow, such as riparian zones. **(Multi-site analysis)**

5. Low-P native pastures generate greater quantities of runoff and more consistently than high-P phalaris-subclover pastures, and the water has lower P and N concentrations **(Wagga)**.

6. At a site producing large quantities of runoff (>100mm/year), only 20% of samples exceeded the healthy stream standard of 0.05 mg P/litre, and there was little relationship between P application rate and P concentration in runoff **(Maindample)**.

7. At a Site producing lower quantities of runoff (20 mm/year), nearly all samples exceeded the healthy stream standard even where low rates of P had been applied **(Vasey)**. Since both Maindample and Vasey have similar soil P values (Table 2), P in waterways appears to be more of a problem where runoff rates are lower and streamflow more erratic.

8. P losses in runoff from sheep-grazed pasture represent only a small financial cost to production (about $0.50/ha.year of fertilizer equivalent) **(Maindample, Vasey)**

9. N losses of up to 10 kg N/ha.year have been recorded from the NE Vic Sites. Whether this is acceptable depends on whether the N ends up in streams. There may be processes that utilise the N prior to its discharge into streams, such as plant uptake by riparian vegetation **(Ruffy and Maindample)**.

Production aspects

10. Carrying capacity increases of between 90% and 193% were achieved by a combination of pasture improvement and fertiliser application. **(Multi-site analysis)**

11. The response of phalaris to additional N was erratic and not economic. N applied in winter caused no additional growth in winter, but caused extra growth in November if soil water was sufficient **(Vasey)**.

12. A phalaris-subclover pasture responded to either N or K. Of these, K is the more economic to apply because of its better residual value. The main implication from this finding is that if a pasture has symptoms of being N-responsive (enhanced growth on urine patches), it is worthwhile to test for K being a limiting nutrient **(Vasey)**.

13. In a Mediterranean environment where kikuyu grass is active in summer/autumn, the application of nitrogenous fertilisers to kikuyu pastures in later spring or preceding summer rain, can provide feed of sufficient quality and quantity to grow livestock outside the growing season **(Esperance)**.

Hunches

Low-P systems on wet spots

Findings that a high proportion of surface runoff is generated from a small proportion of the area led to a recommendation that they should be managed as low phosphorus systems to improve stream quality. (The source areas for surface runoff generation are typically less than 10% of the catchment – personal communication from Guy Geeves, DLWC, Wagga Wagga).

R&D opportunity: Guidelines are needed for how to identify these areas in different geomorphological environments, and the concept needs to be proven at a small catchment scale.

Uncertainties

P and N in runoff water

1. There are as yet no guidelines for P and N concentration in stream water for periods of high flow, which is when surface runoff occurred from the National Experiment Sites. Furthermore, P and N stream quality guidelines are very conservative and may be unrealistic. They are based on pristine streams. There is evidence that disturbed streams (which all 'real' streams now are) can tolerate higher concentrations.

2. There is also no quantification of how much P and N is removed from flowing water between paddock and stream, through processes such as sedimentation and adsorption in farm dams. This is an ***R&D opportunity.***

3. *Intensive systems don't necessarily increase P in runoff water:* While there was a relationship between soil test P and the P concentration in runoff water for Carcoar, Maindample, Ruffy and Vasey, there was no relationship for the North-West Slopes Sites. It was hypothesised in the Theme paper that this was because with higher fertility, more pasture grew and that this improved the surface cover. Another explanation is that relatively little P was added relative to the high total P in these soils (this making a relationship difficult to prove), and that most of the fertiliser response was because of S rather than P. It would be worthwhile to research this further and develop guidelines by which producers can identify the situations where fertiliser application has no net detrimental effect on waterways. This is an ***R&D opportunity.***

Acidification processes

4. Acidification through nitrate leaching was only examined at the NE Victorian Sites, and surrogates (soil mineral N and legume percentage) were used for other Sites. There was poor correspondence between N leaching measurements and these surrogates. Further field measurement of N leaching is recommended for future experimental programs where legume percentages exceed that required for product export (between 10-20%).

Database and model

The Nutrient Theme has been unique in that samples rather than data have been sent from Site teams to the coordinator. Data were usually sent direct from the laboratory to the Theme Coordinator and were thus available for immediate statistical analysis and interpretation. The Co-ordinator did not need to wait for data to become available from Site databases before analysis could commence. All data were, however, forwarded to Site teams to be entered into their Site database.

The model only began addressing nutrient questions late in the Harvest Year, after the results of soil coring data became available in March. By then, there was time pressure on modelling resources from other Themes, and insufficient time for nutrient components of the Model to be fully tested.

R&D opportunity: There is scope to use soil profile and forage mineral nutrient concentration data and collected during the National Experiment to develop the Model into a more reliable tool to address nutrient questions.

Publications

Nearly complete: The only journal publication produced by the Theme has been for the Special Edition of the Australian Journal of Experimental Agriculture, which was submitted in December. A draft of the version submitted to AJEA is attached.

Plan to write: No other papers are planned without new resources.

Could be written: The nutrient cycling components of the SGS Model requires further development and testing. Forage mineral nutrient data and soil profile nutrient data were collected from all SGS Sites to assist with model development, but there was insufficient time in the Harvest Year to use these data with the Model. Soil profile data, needed for initialising nutrient aspects the model, only became available in March, and between March and June there a lot of other competing time requirements placed on the Theme Co-ordinator and Modeller.

Challenges and opportunities for the Theme.

The main challenge in the Nutrients field is that while the impacts of fertiliser on production are well known, the environmental aspects of P and N movement are poorly known, but measurement of these is expensive. There are opportunities for MLA to link with R&D activities funded under other programs, such as the National Action Plan for Salinity and Water Quality, and the CRC for Catchment Hydrology, to achieve positive outcomes for the pasture-based meat production industries.

Acknowledgments

Theme efforts would not have been possible without financial support from MLA, Land and Water Australia, NSW Agriculture, the Victorian Department of Primary Industries, and the Department of Agriculture in Western Australia. We have appreciated the assistance of the State Chemistry Laboratory of Victoria, the WA Chemistry Centre and Andrew Noble of CSIRO Townsville for chemical analyses. Martin Andrew (SGS Theme Coordinator) has provided stimulating thoughts and comments on drafts of the Theme Paper and on this report.

Team membership.

Team membership consists of Malcolm McCaskill (coordinator), Paul Sanford, Anna Ridley, Brendon Christy, Bob White, Bill Johnstone, David Michalk, Sean Murphy and Greg Lodge.

Financial statement

Harvest Year, July 2001 to September 2002

	$ (excl GST)
Analytical costs	
Wagga 0-10 cm cores	122.00
Feed (3 samples)	132.00
Wagga	913.20
Carcoar	6,000.00
Albany	620.80
Vasey	2,836.20
NW Slopes	4,637.00
NE Vic	5,672.40
Esperance	303.00
Esperance	900.00
Subtotal - analyses	21,236.60
Collection costs	
Esperance (casual labour & freight)	906.36
Hamilton (coring rig hire, casual labour)	850.00
Subotal - collection	1,756.36
Total - Nutrient Theme	22,992.96
less Nutrient Theme contract	- 10,000.00
less previous Nutrient Theme carryover	- 2,307.00
less excess funds in Animal Theme	- 2,766.50
less invoiced to Pasture Theme	- 7,919.46
Balance	0.00

Prior to Harvest Year, July 1999 to June 2001

	$
Nutrient Theme income 2000/2001	7,500
Carryover funds from 1999/2000	7,500
Subtotal - income	15,000
Mineral nutrient analyses WA Chem Centre	11,438
Casual labour for dispatch from Feedtest and integration of Feedtest results with mineral data	1,255
Subtotal - expenditure	12,693
Income	15,000
Income less expenditure	12,693
Carryover funds to Harvest Year (income less expenditure)	2,307

Value added by the Harvest Year

Value added to Theme findings: The Harvest Year enabled soil coring of contrasting treatments at each SGS Site and soil analysis, which contributed several Figures and Tables to the Theme paper (the impact of treatments on exchangeable Al, mineral N, total P). The time of the Harvest Year also enabled more thorough analysis and documentation of findings for the scientific press.

How much have Theme findings changed since last year's report ? The report produced in June 2001 was a compilation of nutrient-related findings from Site reports. The Harvest Year has enabled these Site findings to be extended into multi-Site analysis, increasing the rigour of the findings. There have also been several new findings, listed in "Highlights" on page 2 of this document.

What is the added confidence in the findings ? The Harvest Year has enabled researcher hunches to be thoroughly analysed, documented, and published as the Theme paper. Because the results are available as a peer-refereed journal paper, there can be greater confidence when the findings are rewritten for other audiences, such as policymakers, extension staff and farmers.

How has the Harvest Year sped up production of Theme products ? Prior to the Harvest Year, data collected by the Nutrient Theme as part of the minimum protocol and from the Theme budget was designed more to underpin other studies (eg soil cross-site soil tests), or because of opportunity (eg forage mineral nutrients), rather than to address theme questions directly. Without the Harvest Year, there would have been virtually no stand-alone Theme products. Cross-site soil fertility data would have been incorporated into the National Experiment Overview paper, and used as a variate in the Pasture and Animal Theme papers. The Harvest Year enabled the site coring and modelling to be conducted, which contributed over half the data in the Theme paper.

What was the value of the post-docs ? The post-doc was responsible for extracting data from Site databases, some cross-site analyses, and for model runs. The post-doc's value to the Theme was limited by him not having a strong background in nutrients, and not being co-located with the Theme leader. In hindsight the post-doc needed much closer management and direction that he was given.

In hind-sight, how could the Harvest Year have been more effective ?
1. The post-doc needed much tighter supervision, and should have been trained in the use of the SGS model much earlier in his term.
2. Had the tables and Figures in the paper been scoped out earlier, co-authors would have "come on board" earlier with data such as nutrient flow, and less rush of data analysis toward the end.
3. The value of soil coring was limited by it being conducted in spring rather than autumn. This is because funding was not approved until August 2001. Autumn sampling provides a better indication of mineral N that can leach after the autumn break. Had there been approval by March 2001, sampling could have been conducted in autumn.

Effectiveness of the Theme approach

The cross-site generalisations would not have occurred without the Theme approach. Without a Theme role in protocol development, soil fertility information for the National Sites would have been disjointed.

The Theme approach also allowed aspects of the SGS data set that would otherwise not have been published, to be used to support an integrated assessment of the sustainability of nutrient usage in the pasture-based meat industries. Examples include data on the variability of surface runoff generation, total P in the soil profile, and mineral N in the soil profile.

Report completed by Dr. Malcolm McCaskill, Nutrient Theme Co-ordinator, February 2003

13 Dec 2002

SGS Nutrient Theme: environmental assessment of nutrient application to extensive pastures in the high rainfall zone of southern Australia

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Abstract. To assess the production and environmental risks and benefits of more intensive pasture management, 2 or 3 treatments with contrasting fertiliser regimes were selected from each Site of the Sustainable Grazing Systems National Experiment. The assessment used soil coring data, modelling and runoff nutrient concentration data.

Simulations were conducted at 6 of the Sites using long-term weather data comparing nitrate leaching rates from pastures based on annuals, phalaris (*Phalaris aquatica*) and kikuyu (*Pennisetum clandestinium*). Simulated nitrate leaching was greatest for the annual pasture (range 34-58 kg N/ha.year), followed by phalaris (≤ 11 kgN/ha.year) then kikuyu (≤ 3 kg N/ha.year). Soil acidification rates were estimated from the simulated nitrate leaching, and product removal estimated from the stocking rates at each site. Much higher acidification rates were estimated at southern sites such as Maindample and Albany (1.2-4.7 kmol H^+/ha.year) than in northern NSW sites such as Barraba and Nundle (0.2-0.94 kmol H^+/ha.year). This was because of to the relatively low level of nitrate leaching likely in summer dominant rainfall environments coupled with lower stocking rates.

The concentration of P in surface runoff was related to soil fertility at the 4 southern Sites, indicating that greater use of P fertiliser would increase P movement into waterways. There was no relationship between runoff N concentration and soil fertility. There was also evidence of high spatial variation in surface runoff generation. Based on these results, it is recommended that intensification should be accompanied by retiring from production the parts of the landscape that contribute disproportionately to the generation of surface flow.

Introduction

Fertiliser application is a vital component of Australian pastoral agriculture. Superphosphate was initially applied to wheat, and in the 1920s significant responses of introduced pasture plants to phosphate (P) fertiliser were also observed (Donald 1970). However, it was not until the 1920s, when the first subterranean clover cultivars (*Trifolium subterraneum* L.) were released, that State Departments of Agriculture began to promote "sub and super" as a means to intensify pasture-based livestock production. By 1965, the area of pasture receiving superphosphate exceeded 16 million ha (Williams and Andrew 1970). From 1963 to 1977, the federal government supported a bounty that subsidised about 20% of the purchase costs (Davey *et al* 1976), which helped maintain the momentum of using P fertilisers on pastures. The benefits of P fertiliser application included a higher proportion of the pasture species favoured by livestock, higher pasture growth rates, and higher digestibility, all resulting in increased animal carrying capacity, and higher livestock growth rates. In south-eastern Australia, spring-lambing meat enterprises based on heavily fertilised pastures typically have gross margins 33% higher than those where lower rates of fertiliser are applied (Court 1998).

The intensification of livestock production through pasture improvement, fertiliser application and increased stocking rates has had significant impacts on the environment at the paddock and catchment scales. These impacts variously include: soil acidification, contamination of surface and subsurface water, degradation of remaining remnant vegetation, and increased dryland salinity (Gretton and Salma 1996). In the past, these impacts were discounted as being of little importance because they did not initially reduce on-farm production. For example, the effects of increased acid inputs associated with legumes and fertiliser application were evident on lower pH soils in the 1950s (Donald and Williams 1954; Williams and Donald 1957). This issue was not considered important until the 1980s when production losses of pH-sensitive crop and pasture species were recorded (Coventry *et al.* 1987). Appropriate land use was also an issue with problems exacerbated on landscapes that were intensified beyond their capability (Johnston *et al.* 1999).

Increasingly, issues such as water quality and salinity that affect the environment beyond the farm boundary have emerged as major concerns of the community. In response, farmers who were initially focused on remedying on-site environmental impacts that affect their own production and profitability are now also concerned about the off-site consequences of their farming activities (Ridley *et al.* 2003). This shift in farmer attitudes is caused in part by new environmental targets and changes in legislation. In the Murray-Darling Basin, for example, societal concerns have led to the setting of targets for salinity and water quality for each major tributary (Anon. 2000*a*, *b*), and the onus now rests on the agricultural industries to justify and improve their environmental performance. Such pressures contributed in part to the establishment of the Sustainable Grazing Systems (SGS) (Mason *et al.* 2003) and its National Experiment (NE) (Andrew and Lodge 2003).

Within SGS, the Nutrient Theme aimed to quantify the positive and negative on- and likely off-site effects of the intensification of grazing systems in the high rainfall zone (HRZ, >600 mm rainfall) of southern Australia. The productivity benefits of applied P in the SGS NE have been reported for pastures (increased herbage accumulation, increased legume content) by Sanford *et al.* (2003) and for animal production (increased carrying capacity) by Graham *et al.* (2003), so we have explored only some aspects of these in this paper. However, we have explored in more detail the extent to which potential negative impacts were realised. Negative on-site impacts include an increased likelihood of soil acidification, while negative off-site impacts include increased P and nitrogen (N) leaving paddocks in surface runoff, and increased amounts of nitrate-N lost through deep drainage. Another source of potential negative impact is the imbalance between the export of nutrients via product and the inputs of those nutrients into the system.

Materials and methods

At each of the SGS NE Sites, treatments that represented a range of extensive and intensive grazing systems (Table 1) were selected for study. These included contrasting fertiliser input rates, pasture types, grazing methods and grazing management strategies.

All treatments reflected levels of management input found on commercial farms in the vicinity of the respective Sites.

Insert Table 1 near here

Soil fertility

To quantify soil fertility across the Sites, samples (0-10 cm) were collected from low and high fertility treatments in spring 1998 and 2000. Samples were analysed for available P using 1 or more of 3 commonly applied soil tests, namely that described by Olsen *et al.* (1954) (P_{Olsen}), Bray and Kurtz (1945) (P_{Bray}), and Colwell (1963) ($P_{Colwell}$). The Genstat (2000) statistical package was used to derive the following relationships between these soil P tests, based on 82 cross-site samples:

$$P_{Colwell} = exp(0.8295+1.0063\ ln(P_{Olsen})) \qquad R^2=0.92 \qquad (1)$$

$$P_{Colwell} = exp(1.163+0.7944\ ln(P_{Bray})) \qquad R^2=0.81 \qquad (2)$$

$$P_{Bray} = exp(-0.003+1.1032\ ln(P_{Olsen})) \qquad R^2=0.89 \qquad (3)$$

$$P_{Olsen} = exp(0.220+0.8244\ ln(P_{Bray})) \qquad R^2=0.89 \qquad (4)$$

These conversions were applied whenever samples were inadvertently not analysed by all 3 methods. Available sulfur (S) was measured by the method of Blair *et al.* (1991) and available potassium (K) by ammonium acetate extraction (Rayment and Higginson 1992, method 15D3), with a conversion factor to give values equivalent to the method of Skene (1956). Soil pH was measured in calcium chloride using a 1:5 soil:solution ratio (Rayment and Higginson 1992, method 4B2). A list of the symbols used in this paper is contained in the Appendix.

Plant growth indices were calculated from plant-available soil nutrient data to indicate the likelihood of responses. These relationships were based on response relationships reported by Cayley *et al.* (2002), Blair *et al.* (1991 and 1997), and Gourley (1989) for P, S and K, respectively. The equations used were:

$$P\ index = 1-exp(-0.177\ P_{Olsen}) \qquad (5)$$

$$S\ index = 1\text{-}exp(-0.3542\ S_{av}) \quad (6)$$

$$K\ index = 1\text{-}exp(K_{av}(-0.0334\text{-}(0.00041\ \%clay))) \quad (7)$$

where P_{Olsen} = Olsen P, S_{av} = plant-available S, K_{av} = plant-available K, and *%clay* = percentage clay (0-10 cm) taken from the soil descriptions. Each index was calculated from soil test data for the 0-10 cm layer, and ranged between 0 (no growth) and 1 (unrestricted growth). A nutrient was considered non-limiting when its growth index exceeded 0.95. The primary limiting nutrient was considered to be that with the lowest plant response index.

Positive on–site effects of intensification

Animal carrying capacity and proportion of legume. To quantify the benefits of intensification, carrying capacity was estimated in dry sheep equivalent (DSE/ha) using stocking rate data over the period 1998 to 2000, with allowances for carryover feed and supplementary feed as described by Graham *et al.* (2003). In the pastures at each Site the percentage of legume (mainly subterranean clover) by dry weight was used to assess N impacts on the pasture. These pasture assessments were conducted at least 4 times per year by the BOTANAL technique (Tothill *et al.* 1992), with more frequent assessments during spring when pasture growth was more rapid. Further details are given by Andrew and Lodge (2003) and relevant Site papers in this special Journal issue.

The percentage legume required to balance N export in product, termed the 'benchmark legume percentage' (*B*, %) was estimated as:

$$B = 100\ E \times C/(N_{fix} \times G) \quad (8)$$

where *C* = carrying capacity (DSE/ha), *G* = herbage accumulation (t/ha.year), *E* = N exported in wool and meat (kg N/DSE.year), and N_{fix} = kilograms of N fixed per tonne of above-ground legume growth. Values of *C* and *G* for the SGS NE were reported by Graham *et al.* (2003) and Sanford *et al.* (2003). The value of *E* was estimated as 1 kg N/DSE.year based on the expected export of N in wool and meat from a ewe-lamb enterprise (McCaskill and Cayley 2000). Data from Peoples *et al.* (1998) indicate that each tonne/hectare of above-ground legume growth contains 25 kg N/ha that is fixed from the atmosphere. A glasshouse experiment by McNeill *et al.* (1997) found that in addition to N in the plant tops, a further 11-15% was contributed in the roots and root exudates. The value of N_{fix} was therefore estimated as 25 x 1.12 = 28 kg N/ha fixed for each t/ha of legume growth. An alternative method of estimating G used a feed intake I (kg/day) of 1 kg of dry matter per DSE per day, and assume a pasture utilisation rate U (kg eaten per kg grown) so that:

$$G = 365\, I \times C/1000\, U \qquad (9)$$

A utilization rate of 50% was assumed for the North-West Slopes Sites and Wagga Wagga, and 80% for other Sites. This method was used for the Wagga Wagga, Maindample, Ruffy, and Esperance Sites, and some treatments on North-West Slope Sites, where pasture growth rate was not measured.

Negative on-site effects of intensification

Nitrate leaching. To examine the potential impact of pasture management on the rate of NO_3^- leaching, using information from across a range of Sites, simulations with the SGS Pasture Model (Johnson *et al.* 2003) compared 4 pasture types with widely different abilities to control NO_3^- leaching: (1) a redgrass (*Bothriochloa macra*)- subterranean clover pasture to represent a summer active species of moderate control of NO_3^- leaching, (2) an annual pasture consisting of annual ryegrass (*Lolium rigidum* Gaudin) and subterranean clover to represent poor NO_3^- leaching control, (3) a phalaris-subterranean clover to represent intermediate control, and (4) a kikuyu (*Pennisetum clandestrinum* Hochst. ex Chiov.)-subterranean clover pasture to represent the best possible control of NO_3^- leaching using a pasture species. These simulations were conducted using climate data for 6 of the SGS NE Sites for 31 years (1971-2001) obtained from the SILO database, as described by Andrew and Lodge (2003). Soil properties derived from the Yellow Sodosol at Vasey (representative of a wide area of the HRZ) were used for all simulations. Nutrient concentrations in the soil profile were initialised using data from the soil cores collected from control treatments in 2001. Further details of these simulations were provided by Andrew and Lodge (2003).

To determine the cumulative impact of treatments on mineral N in the soil profile, soil cores were collected from at least 2 contrasting treatments at each Site in 2001. Cores from the Maindample and Ruffy Sites were sampled in April 2001, while the remaining Sites were sampled between October and December 2001. Cores were collected to a depth of 1.2 m at Manilla, Barraba, Nundle (3 cores per treatment), Maindample (minimum of 20 cores per treatment), Ruffy (at least 14 cores per treatment) and Vasey Sites (12 cores per treatment); to 1.0 m at Carcoar (9 cores per treatment) and Wagga Wagga (2 cores per treatment); to 1.5 m on the kikuyu treatment at Esperance; and to 0.75 m on the annual treatment (5 cores per treatment). Cores were dissected to give samples at depths of 0-10 cm, 10-20 cm and then in 20 cm increments, and analysed for mineral N [the sum of nitrate-N (NO_3^--N) and ammonium-N (NH_4^+-N)]. Mineral N was extracted in 1 M KCl solution and analysed by colorimetry (Rayment and Higginson 1992, method 7C2). Where concentrations were below the laboratory detection limit (0.25 mg/kg and 0.7 mg/kg for NO_3-N and NH_4^+-N, respectively), a value of 50% of the detection limit was substituted in statistical analyses. Data from the Barraba, Manilla, Carcoar, Maindample, Ruffy, Vasey and Esperance Sites were statistically analysed by a linear mixed model that included cubic splines of depth (Verbyla *et al.* 1999). This form of analysis was designed to detect treatment differences across all depths, and differences in the distribution of N within the profile. The model was fitted to data for nitrate and total mineral N to test for treatment effects, while allowing for random effects of plot or sampling position. At the Maindample, Ruffy and Esperance Sites, plots were not replicated but sampling position was replicated, and differences may have been due to position in the landscape. Statistical analysis was not possible for Nundle and Wagga Wagga, due to the unreplicated experimental or sampling designs at those Sites.

The soil core samples were also analysed for exchangeable aluminium (Al^{3+}), using the method of Gillman and Sumpter (1986). Exchangeable Al^{3+} was expressed as a proportion of the effective cation exchange capacity (ECEC), defined here as the sum of Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+} (Gillman and Sumpter 1986).

Soil acidification. To assess the sensitivity of soils to acidification, we measured the pH buffering capacity (*pHBC*, Noble *et al.* 1997) on surface soil cores (0-10 cm) collected in spring 2000 from sampling positions representing soil typical of a Site. Since the 4-year experimental period was too short to generate measurable changes in pH, we estimated the time for pH decline to occur using the soil bulk densities from the Sites and the equation developed by Helyar and Porter (1989):

$$T = \Delta pH \times pHBC \times BD \times V/A \qquad (10)$$

where T = time (years), ΔpH = change in pH; $pHBC$ = pH buffering capacity (cmol H^+/kg.pH), BD = bulk density (10^3 kg/m^3), V = soil volume for 1 ha to 10 cm depth (10^3 m^3) and A = acidification rate (10^5 cmol H^+/ha.year).

We did three calculations. First the acidification rate was calculated from the sum of animal product removal and modelled nitrate leaching results. Product removal was estimated from the stocking rate values, and a conversion factor of 0.6 kmol H^+ per 10 DSE (Slattery *et al.* 1991). Nitrate leaching (kg N/ha.year) estimates as derived for each site from the SGS model were converted to kmol values (dividing kg N by 14 to convert to kmol H^+). Product removal and nitrate leaching values were then summed to estimate the acidification rate. The simulated annual pasture was used to represent the Control treatment for the Maindample, Vasey and Albany Sites, and the simulated redgrass (*Bothriochloa macra*) pasture for the Control treatment at Barraba, Carcoar and Wagga. Simulations for Barraba were used for Manilla and Nundle Sites, and Maindample simulations for Ruffy.

Next, we estimated the time to change pH by 1 unit (assuming that acidification only occurred in the top 10 cm), by solving equation 10 for time and the acidification rate as calculated above. Finally we estimated the time for soils to acidify to pH 4.2, through solving equation (10).

A pH of 4.2 was used because this is the level below which high concentrations of exchangeable aluminium may significantly depress growth of phalaris (*Phalaris aquatica* L.) in some soils (Ridley *et al.* 1992).

Negative off-site effects - P and N in surface runoff

Data on the concentration of total P and N in surface runoff were available for Sites on the North-West Slopes of New South Wales and at Carcoar, Wagga Wagga, North-East Victoria and Vasey. At most Sites, water quality data were collected from 1998 to 2000, but at Carcoar they were only available for the 12 months from September 2001 to August 2002. Runoff plots at the North-West Slopes and Carcoar Sites had a surface area of 0.01 ha, and were set within larger grazing plots, whereas at Wagga Wagga and North-East Victoria small catchments of 1.8 to 13.7 ha were used for runoff measurements. At Vasey, runoff was measured on a separate set of 0.5 ha plots adjacent to the main experiment. Water samples were collected within 1-2 days of each runoff event and were either analysed immediately, or preserved in acid or frozen until analysis. Samples for total P were digested using persulphate (Hosomi and Sudo 1986). At some Sites, more detailed fractionation was conducted, but in this paper only total P and N are reported. Further details of sampling and analytical methods at each Site were given by Murphy (2002), Michalk *et al.* (2003), Johnston *et al.* (2003), Ridley *et al.* (2003) and Melland (2002), respectively. For each Site, the flow-weighted average P concentration was calculated for each plot and year. Where there were more than 5 flow events for a plot in each year, a flow-weighted standard error was calculated by bootstrapping using S-Plus 2000 (MathSoft, Inc. 1999), using events and replicates (where available) to estimate variance. Runoff quantity was compared with records from nearby stream gauging stations, and runoff quality was compared with stream quality guidelines (Anon. 2000*c*). The 31-year simulations for the phalaris-subterranean clover pasture were used to assess the timing of surface runoff and deep drainage events because these are drivers of P and N movement. .

To determine the relative risks of P loss through erosion across the SGS NE Sites, the soil core samples collected in 2001 were also analysed for total P by nitric-perchloric digestion followed by Inductively Coupled Plasma Emission Spectroscopy using the 177.495 nm spectrum (Carter 1993). Potential P losses through erosion were estimated assuming the loss of 1 mm of soil from the 0-10 cm layer and a Phosphorus Enrichment Ratio (PER, Sharpley 1980) of 3.5.

Results and Discussion

Positive on-site effects – the benefits of improved fertility

Surface soil fertility. At most Sites, the plant availability indices (Equations 5-7) indicated that P was the primary limiting nutrient (Table 2), followed by S at 2 sites (Barraba and Manilla). The P index for High treatments was less than the 0.95 threshold growth limiting value at Manilla, Maindample, Ruffy and Esperance (kikuyu). The S index was also below this threshold value at Manilla, Carcoar, Ruffy and Esperance. Only the Barraba, Wagga Wagga, Vasey and Albany Sites had both non-limiting levels of P and S on the High treatment. Levels of K were sufficient to ensure this nutrient was not the primary growth limitation. However, at Carcoar Maindample, Vasey, Esperance and Albany Sites, soil K status was marginal (Table 2), and potash would normally be recommended when deficiencies in other nutrients were fully corrected. It is likely that additional gains in carrying capacity could have been obtained by correcting deficiencies for treatments where P, K and S were limiting.

Insert Table 2 near here

Carrying capacity increased between 18% and 215% through intensification (Table 3). The magnitude of this increase was greatest where the control was an unimproved system, and was compared with a fully intensified system. At Albany for example, the Control was at a moderate level of fertility, and the pasture dominated by introduced species suited to high fertility (Tables 1 and 2). Only a modest gain in carrying capacity of 47% was made through further intensification. At Carcoar, the High intensity treatment reported here achieved only a 39% improvement in carrying capacity relative to the unfertilised native pasture Control. The High treatment at Carcoar was a flexibly grazed sown pasture with a lax grazing regime designed to maximise pasture perenniality and water use. However, another sown pasture at Carcoar designed to maximise animal production had a carrying capacity of 13.6 DSE/ha in 2001, which was nearly 90% higher than the Control (Michalk *et al.* 2003). Further benefits of improved fertility were detailed in the Pasture, Animal and Water Theme papers (Sanford *et al.* 2003; Graham *et al.* 2003; White *et al.* 2003).

Legume contents accounted for <25% of herbage mass across all Sites apart from the Vasey Medium treatment, and the annual pastures at Albany and Esperance (Table 3). At Nundle, Maindample, and Vasey, where the most intensive treatment was based on a sown phalaris-subterranean clover pasture, the legume percent increased substantially relative to the control (Table 3). However, at Esperance and Albany where the intensive treatment was based on kikuyu, legume content decreased by 50% and 32%, respectively, relative to the annual pasture. At Barraba and Manilla, the intermediate treatment, which consisted of rotational grazing of native grasses and naturalised legumes, resulted in legume contents <1%.

Insert Table 3 near here

At 5 Sites the legume content required to balance N exports (benchmark legume percentage) was calculated (Table 3) from measured herbage accumulation. Three of these

Sites (Barraba, Manilla, and Carcoar) had legume contents below that for N balance, while the Vasey Medium and the annual and kikuyu pastures at Albany were very much above the benchmark. Where herbage accumulation was estimated from carrying capacity and utilisation rate using Equation (9), the benchmark legume percentage was calculated to be 4.9% for a utilisation rate of 50% (typical of northern pastures), or 7.8% for a utilisation rate of 80% (typical of southern intensive systems). Most of the remaining Sites had legume contents around these benchmarks apart from the intensive treatment at Nundle, where legume comprised 18% of the pasture.

Negative on-site effects

Impact of management on N leakiness. Nitrate leaching predicted by the SGS Pasture Model is shown in Figure 1. Leaching from the annual pasture ranged from 34 kg N/ha.year at Wagga Wagga to 58 kg N/ha.year at Carcoar. The redgrass-subterranean clover pasture was well below the annual pasture at Barraba and Wagga Wagga, but had similar estimated leaching to annual pasture at Carcoar, Maindample, Vasey and Albany. This is because redgrass growth would be under a strong temperature constraint during the main rainfall season at the latter sites, and that the simulated pastures would be dominated by subterranean clover, and thus similar to the annual pasture. At all Sites NO_3^- leaching was much less for the perennial phalaris-based pasture (≤ 11 kg/ha.year) and smaller again with the deeper-rooted kikuyu pasture ≤ 3 kg N/ha.year). Some of this effect was because the perennials reduced the quantity of water leaking below the root zone (White *et al.* 2003).

The only Site where simulated NO_3-leaching was compared with measured data was at Maindample. Here, NO_3- leaching by deep drainage in the Medium and High treatment averaged 1 and 4 kg N/ha.year respectively between 1998 and 2000 (Ridley *et al.*

2003) compared to the model estimate for the phalaris pasture of 3 kg N/ha.year for the same period. For the Control treatment, the measured leaching loss was 4 kg N/ha.year for 1998-2000, whereas the simulated loss from annual pasture averaged 34 kg N/ha.year. The SGS Pasture Model is thus likely to have over-predicted NO_3^- leaching from annual pastures. Further evidence that the SGS model has over-predicted NO_3^- leaching comes from work in southern N.S.W. where Ridley *et al.* (2001) measured N losses of 9 and 6 kg N/ha.year under unlimed annual and perennial pastures over a 3 year period. Higher losses (up to 33 kg N/ha on limed annual pasture) occurred in a particularly wet year.

Mineral N. The quantity of mineral N in the top 1 m of the soil profile was higher at Maindample and Ruffy, where soils were sampled in autumn, than at the other Sites that were sampled in spring, except for Vasey, Medium input (Table 4, Fig. 2). Sites sampled in autumn also had a greater proportion of their mineral N as NO_3^-. Because of this difference in sampling time it was not possible to compare among Sites, other than to note that the results confirm previous work of mineral N being higher in summer-autumn than spring (Joshua *et al.* 1998; Ridley *et al.* 2001). Instead, treatments were compared within Sites. At Ruffy there was significantly more NO_3^- and mineral N in the Medium and High treatments than the Control (P <0.001). The Esperance Site also had clear treatment differences, with significantly less NO_3^- and mineral N in kikuyu pastures than annual pastures (P <0.001). At Barraba there was significantly (P <0.001) more NO_3- in the profile of the High treatment (native pasture + sub clover) than the Control, but no significant differences in total mineral N. Vasey had significantly more total mineral N in the Medium treatment than the High (P <0.001). At other Sites where statistical analysis was possible (Manilla, Carcoar and Maindample), treatment differences were not significant. No statistical analysis was possible on data from Nundle or Wagga Wagga, but at these Sites treatment differences were below those required for significance at other Sites.

Insert Table 4 near here

Insert Fig 2 near here

At all Sites there was a significant ($P < 0.001$) effect of depth on mineral N distribution within the soil profile (Fig. 2), with highest concentrations in the top 10 cm, except for Carcoar and the Vasey Medium treatment where there was evidence of accumulation deeper in the profile. At Vasey, full intensification through greater P fertility and rotational grazing resulted in a relatively low mineral N concentration under the High treatment of 55 kg N/ha compared with 105 kg N/ha under the Medium (Table 4). The reasons for this are likely to be due to rotational grazing favouring the phalaris component, thus resulting in a greater capacity of N uptake (and hence lower measured mineral N) than the Medium treatment (Chapman *et al.* 2003).

There was little evidence from this study that the higher intensity treatments were any more at risk of nitrate leaching than the controls. There was, however, some evidence that some of the intermediate treatments appeared to carry a higher risk than either control or fully intensified systems. The only Sites and treatments where N fixed was substantially more than N exported in product were the Medium pasture at Vasey and the annual and kikuyu pastures in Western Australia (Table 2). There was evidence that the kikuyu-based pastures in Western Australia reduced the risk of N leaching compared with the annual pasture system, because of their lower legume percentages and soil mineral N content

(Tables 3 and 4). For all other Sites and treatments, legume percentages were generally close to or below that required to balance N export in meat and wool.

While high levels of mineral N can be a warning sign of potential NO_3- leaching problems, there are compensating mechanisms within pastures whereby fertility-responsive species (e.g. chicory) can utilise the increased mineral N stores early in the growing season. To be more certain of the longer term sustainability of the N cycle for intensified systems requires more detailed measurements than were made in this study. Measurements should include soil solution sampling for NO_3^- below the root zone, and soil coring in autumn, as were conducted at the Maindample and Ruffy Sites (Ridley *et al.* 2003).

Soil aluminium: Exchangeable Al^{3+} comprised >20% of ECEC at Carcoar, Maindample and Ruffy (Fig. 3) and <7% at other Sites. Highly acid-sensitive plants experience growth limitations at Al^{3+} levels of 8%, and only highly acid-tolerant species grow without limitation at Al^{3+} levels >21% (Fenton 1995). At the Carcoar Site, for example, the more acid-tolerant cocksfoot (*Dactylis glomeratum* L.) became dominant even though a cocksfoot phalaris pasture had been sown (Michalk *et al.* 2003). Al toxicity is already a major constraint for pastures in North-East Victoria and southern and central New South Wales, and to overcome this, lime is recommended for establishment and maintenance of introduced species such as phalaris (Ridley *et al.* 1992). The high Al^{3+} at the Sites in this region indicate that further acidification would lead to large decreases in production.

Insert Fig. 3 near here

Acidification. Due to the time frame of the experiments, pH differences between treatments were generally small, except at Maindample and Carcoar where lime application on the high intensity treatments increased pH values (Table 5). Soil pHBC values ranged from 0.9 cmol H^+/kg soil at Albany to 5.3 cmol H^+/kg on the Ruffy High treatment. Except for the sandy-textured soil at Albany, which had very low pHBC values, buffering capacities were lower for the northern Sites (Manilla, Barraba, and Nundle) than the southern Sites.

Insert Table 5 near here

High acidification rates (over 4 kmol H^+/ha.year) were estimated on Control treatments at Carcoar, Maindample and Ruffy (Table 5), due to the large amount of nitrate leaching estimated from the SGS model. Lowest acidification rates were estimated at the northern NSW sites (0.2-0.9 kmol H^+/ha.year) due to low nitrate leaching estimated from the modelling and comparatively low stocking rates.

The time for a pH decline of 1 unit varied between 3 and 117 years (Table 5). Longest times occurred at Barraba and Manilla Control sites due to the low acidification rates. Time for a 1 unit pH decline was also high on the Wagga Wagga High site (86 years), due to a higher *pHBC* than for northern NSW sites in addition to a low acidification rate. Shortest times occurred at Albany, the Carcoar Control, Maindample Control and Ruffy Control treatments (all less than 15 years) due to the high acidification rates (resulting from high estimated nitrate leaching), and in the case of Albany, due to the very low *pHBC* values.

The time to acidify to pH 4.2 was primarily dependent on the current pH value, but was exacerbated by low *pHBC* values. Unlimed Control soils at Maindample and Ruffy were already at pH 4.2. Other sites with less than a 10 year time frame to acidify to pH 4.2 were the Carcoar Control, Vasey High and Albany.

Since the SGS model is likely to have over-predicted the nitrate leaching from the annual pasture, because of the discrepancies between measured results at the Maindample Site, acidification rates would also be over-estimated for this treatment. Nevertheless, the conclusions about the severity of the soil acidity problem still hold, as without lime Maindample and Ruffy already have a soil pH of 4.2 and thus are likely to be limited by Al toxicity.

The rate of soil pH change depends on the rate of net acid input and the pHBC of the soil. In grazing systems, the rate of net acid input reflects the balance between the rate of acid input from the atmosphere, weathering of soil minerals, leaching of nitrate, and input of supplements, and rate of removal through plant and animal products. The pHBC values reported here are a measure of the short-term resistance of the soil to acid inputs (or alkali removal), determined over a 1-week laboratory equilibration period. The method underestimates the contribution of slow reactions through dissolution of aluminium and silica (Noble *et al.* 1997). For this reason, the actual times to acidify the soil are likely to be greater than the estimates in Table 5.

Several studies have reported pHBC values under pastures in the HRZ in southeast Australia, such as that of Ridley *et al.* (1990*a*) who reported values ranging between 2.6-6.0 cmol H^+/kg (mean 3.6). Results from Carcoar, Wagga, Maindample, Ruffy and Vasey all fall within this range. The pHBC values from the North-West Slopes Sites and Western Australia Sites were less, falling within a range of 1.4-2.1 cmol H^+/kg for Sites in North-West Slopes and 1.2-2.4 cmol H^+/kg for Western Australia Sites. Noble *et al.* (1998) reported pHBC values of 2.4 cmol H^+/kg, under leucaena (*Leucaena leucocephala*) forage tree pasture systems in south-eastern Queensland, but other than this, pHBC data for northern pastures are scarce.

Timing of deep drainage. For a simulated phalaris-based pasture, the SGS Pasture Model predicted <5 mm/month of deep drainage for the Barraba and Wagga Wagga Sites (Fig. 4). At other Sites there was a clear peak of drainage in late winter and early spring when soils were most likely to be saturated. These simulations were for drainage below a depth of 3 m, whereas the simulated rooting depth of phalaris was 1.2 m. For a saturated hydraulic conductivity of 60 mm/day (Melland 2003), the simulated water front would therefore take 30 days to move from the 1.2 m to 3 m depths. For this reason, the water front would leave the root zone of phalaris about 1 month earlier than the drainage peaks shown in Fig. 4. Deeper-rooted species thus have greater opportunity to capture deep NO_3^-.

At Victorian Sites, the autumn break occurs between early March and early June (Clark *et al.* 2003), leaving a period of 1-4 months for plants to recover from dormancy, commence growth and take up NO_3^- prior to the commencement of drainage. An early autumn break thus allows greater opportunity for plants to grow and take up N, as opposed to seasons where the break occurs later.

Insert Fig. 4 near here

Negative off-site effects

P in surface runoff. The concentration of total P measured in runoff ranged from 0.15 to 1.99 mg P/L across the Sites and seasons represented (Table 6). The highest values (> 1 mg P/L) occurred at Barraba in 2000 and on the Maindample High treatment in both 1998 and 1999. At the North-West Slopes Sites, there was no relationship between soil fertility, as measured by the Olsen P value (0-10 cm), and the P concentration in surface runoff. There was, however, a strong relationship (R^2=0.87) between total P and suspended sediment concentration (Murphy 2002). Both these variables were strongly related to the quantity of runoff. In the long-term, treatments with greater ground cover and biomass would generate less surface runoff, and consequently less P movement. Other studies in the same region by Lang and McCaffrey (1984) found that for individual events, ground cover was not correlated with erosion, but that in the long-term, soil loss rates were correlated with ground cover.

Insert Table 6 near here

At the southern Sites (excluding Wagga Wagga, for which flow-weighted nutrient concentration data were not available), there was a significant relationship ($P < 0.001$) between soil fertility and runoff P concentration ($[P]$, mg P/L):

$$[P] = -0.12 + 0.051\, P_{Olsen} \qquad R^2 = 0.50; \qquad n = 30 \tag{10}$$

This relationship encompassed a wide range of pasture, soil, slope, and runoff event types including high-intensity storms producing infiltration-excess runoff, and long duration saturation-excess runoff during winter (Gregory and Walling 1973). Similar relationships have been developed from other studies (*e.g.* Nexhip and Austin 1998). Melland (2002) found a stronger correlation ($R^2 = 0.57$) between runoff P concentrations and soil P fertility (0-5 cm Olsen P) for data pooled from the Maindample, Ruffy and Vasey runoff Sites. Furthermore, as fertility level increased, the soluble P concentration in the runoff increased, but the particulate P concentration did not. At Vasey for example, the proportion of dissolved reactive P (the form most readily available for algal uptake) increased from 54% to 74% of total P, as P fertility increased (Melland *et al.* 2001).

Intensification through higher P fertility therefore increased the proportion of runoff P that was readily available to aquatic organisms and most liable to cause eutrophication problems.

These findings were consistent with the hypothesis that detachment of fine particles is the dominant process in the northern Sites, contrasting with the southern Sites where a combination of dissolution and fine particulate movement are the dominant processes. Therefore in environments where particulate P losses dominate runoff, a response in runoff concentrations to P fertility may not occur because of compensating mechanisms such as increased ground cover that both increases water infiltration and reduces the kinetic energy of water flowing across the ground surface. However in environments where soluble losses dominate, intensification through improved P fertility can be expected to increase P losses. This has important implications in southern Australia, especially Victoria, where land prices are relatively high and there is pressure for intensification to maintain viability.

Concentration of total P in surface flow from all Sites (Table 6) exceeded the maximum desirable P levels for healthy streams, above which action should be taken to assess if there is a potential impact (Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Anon. 2000*c*). This is cause for concern for both extensive and intensive pasture-based livestock production. However, these levels are set at conservatively low values, and are intended for use during low flow conditions when surface flow from paddocks would not be a direct contributor to streamflow. When water is running over the ground surface the creeks are likely to be flowing strongly. Nevertheless, where P concentrations exceed these levels it is recommended that in-stream monitoring and research be undertaken on minimally disturbed reference systems to more accurately define water quality standards for each system (Anon. 2000*c*).

N in surface runoff. Large variations in N concentration were observed between years within Sites (Table 6). Average N concentrations always exceeded the stream trigger levels even for native pasture treatments, often by more than 10-fold (Table 6). There was no consistent relationship between level of intensification and the N concentration of runoff water, except at Ruffy where the concentration from the Medium level of intensification exceeded the Control (Table 6). Indeed, at Ruffy, the runoff N concentration for the Medium treatment also exceeded that of the highest level of intensification in 2000. Thus N concentration in run-off would appear to be largely independent of management, which makes empirical sense, given that rain falling on pastures does not come into contact with the NO_3^- in soil, unless the rain infiltrates soil. The data indicate that there is little a landholder can do via paddock management to achieve these water quality targets, and that more accurate definition of the target levels is warranted.

Runoff generation: The annual runoff rates measured for the plots at the North-West Slopes Sites, Carcoar, North-East Victoria and Vasey was often well below that recorded in the reference streams (Table 7). There was also high spatial variation in surface runoff generation (data not shown), through variation in topography, soil characteristics, and surface cover. At the Vasey runoff Site, for example, an area of convergent topography representing less than 2% of the total landscape contributed up to 80% of the runoff (Melland *et al.* 2001). In the SGS NE there was no attempt to define which parts of the landscape contributed to streamflow. However, other Australian and United States studies have found that areas of convergent topography and close to drainage lines contribute much of the surface runoff (Barling *et al.* 1994, Western *et al.*1999, Gburek and Sharpley 1998), while areas far from drainage lines rarely contribute directly to streamflow. In choosing experimental locations for the SGS NE, drainage lines were avoided because of high spatial variation, and because these parts of the landscape are not often converted to sown pasture. On a catchment scale, discharge of groundwater would contribute additional streamflow, as would flow from parts of the catchment with higher rainfall. For example, the catchment where the Nundle Site was located exhibited steep rainfall gradients (data not presented), with areas higher in the catchment than the SGS NE Site likely to contribute most of the flow to the reference stream. Thus, in order to minimise the P accessions in whole sub-catchments, there is scope to identify source areas contributing most of the runoff, and to manage these as low-P systems. This approach is currently used as the basis of extension programs to reduce P levels in waterways in the United States (Sharpley *et al.* 1999), and could easily be modified to achieve similar outcomes in Australia.

Insert Table 7 near here

Recommended practices for the meat and wool industries need to have at least no greater negative impacts on the environment than the current standard practice. At the North-West Slopes Sites, higher fertility and pasture accumulation increased ground cover, thus off-setting direct effects of labile soil P on runoff P concentration. At the southern Sites, nearly all runoff occurred at times of high ground cover on all treatments, and yet higher soil fertility was associated with increased P concentration in surface runoff. To compensate for this effect, intensification of pasture-based systems needs to be accompanied by measures that maximise the trapping of nutrients, and the dilution of flow with runoff from low-P areas (Melland 2002). Much of this would occur anyway through the presence of farm dams on drainage lines, which trap nutrients, and fencing off areas adjacent to drainage lines. Indeed, it is often only through intensification that landowners can afford to fence off and retire from production the riparian areas most at risk of contributing to P movement into waterways.

Total P in the profile. Three distinct patterns of total P were observed in the soil profile (Fig 5). At Carcoar, Maindample, Ruffy and Vasey, P concentrations were high in the top 10 cm (>200 mg P/kg), and lower in the remainder of the profile (<100 mg P/kg). At Esperance, P concentrations were low throughout the profile (<20 mg P/kg), whereas at the North-West Slopes and Wagga Wagga Sites, P concentrations were consistently high throughout the profile (125-595 mg P/kg).

Insert Fig 5 near here

The high total P concentrations in the top 10 cm highlight the importance of protecting topsoil from erosion. Comparison with Table 2 indicated that only 1.5-30% of topsoil P was in plant-available forms. Much of the unavailable P would be tightly bound to iron-containing minerals such as haematite and goethite (Taylor and Schwertmann 1974). While this P is regarded as being unavailable to plants, transport of the Fe-containing minerals into waterways following erosion can cause P to be released in soluble forms capable of sustaining algal blooms (Boström et al. 1988). A similar concentration of P was observed in the Long-term Phosphate Experiment at Hamilton, Victoria, where 55% of P applied over an 18-year period accumulated in the top 10 cm of soil, doubling the total P concentration from 340 to 680 mg/kg (McCaskill and Cayley 2000). Within the 0-10 cm layer, 62% of total P was in the top 5 cm, indicating that P was concentrated near the surface. The only SGS NE Site where 0-5 cm samples were collected (Carcoar) showed a similar level of concentration toward the surface (data not shown).

Total soil P concentrations were highest for the North-West Slopes Sites (Fig. 5), where the risk of surface water movement in summer was the greatest of all SGS NE Sites. Indeed, the Nundle Site is located upstream of the Chaffey Dam, which has experienced major algal bloom problems since its opening in 1979. Detailed studies have traced the dam sediments to streambank erosion (50%) and sheet erosion of basalt-derived soils from an area comprising <1% of the total catchment (Caitcheon *et al.* 1994). These soils contain up to 10,000 mg P/kg, which is much greater than the 425 mg P/kg in the topsoil of the Nundle Site. Thus the P in the dam sediments was related to natural sources rather than to fertiliser inputs.

Because P is held mainly on clay particles that are more readily moved by water than the larger particles (Sharpley 1980), the total P concentration of eroded material is often greater than that of the soils from which it is derived. Calculation of the PER using total P in the 0-10 cm layer accounts for the tendency for P to be concentrated toward the top of this layer, where there is greatest risk of it being displaced by moving water. Melland (2002) measured PERs (based on 0-10 cm total P) of 2.0 at Vasey and 4.5-8.0 at Maindample. Assuming a PER of 3.5 in the middle of this range, potential P losses through erosion of 1 mm of soil were calculated to range from 9.5 kg P/ha at Carcoar to 31.9 kg P/ha at Barraba (Table 8). Comparison with P loads in runoff measured during the SGS NE showed this was equivalent to between 31 and 1370 years of runoff P losses under well-managed conditions. Johnston *et al.* (1999) have noted that most of the runoff and sediment lost over time from plots and catchments occurs in response to infrequent high intensity events, such as heavy drought-breaking rain. Thus the 1998-2000 data (Table 8), which did not encompass the infrequent high-intensity events and showed low rates of P loss due to water movement, are almost certainly underestimates of the the longer term rates of loss.

Insert Table 8 near here

Timing of runoff. Mean monthly surface runoff, as predicted by the SGS Pasture Model over a 31-year period for a phalaris-based pasture on a Yellow Sodosol, showed a summer peak at Barraba, summer and spring peaks at Carcoar, and peaks in late autumn and early winter at the other Sites (Fig. 6). At southern Sites, coincidence of the runoff peak with the period when pasture mass is likely to be at a minimum emphasised the need to maintain at least 70% ground cover at all times of the year to reduce the risk of erosion (Costin 1980). These conditions are more likely to be met by perennial than annual pastures; indeed, a study at Wagga Wagga by Heng *et al.* (2001) showed that perennial phalaris-based pastures carried greater ground cover in the autumn than annual pastures, and had less surface runoff in autumn.

Insert Fig. 6 near here

General discussion

The data set collected within the Nutrient Theme of the NE was not as comprehensive as that collected in Water, Pastures and Animal Themes. This was due both to reasons of expense and that nutrient expertise was not strong across all Site teams. Additionally, analysis of the SGS model results with the limited measurements did not occur until 'late in the day' within SGS. In hindsight, placing greater emphasis and generating ownership of the importance of nutrients with in SGS and integrating modelling analysis with Site data was warranted.

There are still significant gaps in our understanding of how nutrients applied to pastures impact on the environment. Firstly, the stream water standards for P and N appear to be set too conservatively, such that even if no nutrients are applied the water quality standards are not met. More appropriate standards need to be determined, together with management systems that can meet the new standards. Secondly, findings that only a small proportion of a catchment contributes to surface runoff need to be developed into a decision support framework whereby landholders can identify the contributing areas, so the non-contributing areas can be managed primarily for productive purposes. Thirdly, the lack of evidence in this paper that intensive pasture systems leak any more NO_3^- than unimproved systems is based on limited data, most of which was collected for other purposes. More intensive study of NO_3^- movement is necessary, particularly for pastures that exceed the benchmark legume percentage.

Conclusions

For N and acidification issues, there was little evidence from this study that fully intensified pasture systems were any less sustainable than the control, unimproved systems. This was because the perennial grass in the intensified systems was able to exploit the extra fertility, particularly N. There was, however, evidence that intermediate levels of intensification (that encourage a high percentage of legume), carry a higher risk of N loss and acidification. The risk factors include much greater amounts of N fixed than required to balance product export in meat and wool, and greater stores of mineral N in the soil profile. For P issues, there was evidence from southern Sites that the higher the soil P fertility, the greater the concentration of P in runoff waters. The off-site negative impacts of P loss need to be balanced against the 2-3 fold increases in carrying capacity of high P input systems relative to unimproved control pastures (Table 2). It is often only through capturing the positive benefits of intensification that landowners can afford to fence off and retire from production the riparian areas most at risk of contributing to P movement into waterways. Clearly the area of nutrient loss and off-site impacts from agricultural land use will become increasingly important. Research into nutrient losses conducted at a realistic scale is expensive and needs to be conducted over a range of seasons, as major events occur only occasionally. This will be a major challenge given the current funding constraints and short-term nature of field based agricultural research being conducted in Australia generally.

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List of Figures

Fig. 1. Long-term nitrate leaching predicted by the SGS Model.

Figure 2 Mineral N concentration in 2001 at (*a*) Barraba, (*b*) Manilla, (*c*) Nundle, (*d*) Carcoar, (*e*) Wagga Wagga, (*f*) Esperance, (*g*) Maindample, (*h*) Ruffy, and (*i*) Vasey. Nitrate-N is represented as dashed lines with open symbols, and mineral N (nitrate + ammonium) as solid lines and filled symbols. □ ■ Control ○●Medium Δ▲ High treatment. For Esperance ○● Annual Δ▲ Kikuyu treatment.

Fig. 3. Aluminium as a percentage of ECEC ± SE for (a) northern sites ◆ Barraba, ▲ Manilla, □ Nundle (b) Carcoar ◆ limed (no SE) and ,Δ unlimed, and (c) southern sites ■ Maindample, ▲ Ruffy, ○ Vasey and ◊ Esperance.

Figure 4. Monthly drainage predicted by the SGS model over a 31-year period for ◆ Barraba, Δ Carcoar, □ Wagga Wagga, ■ Maindample, ○ Vasey, and ● Albany.

Figure 5. Total P in the soil profile for (a) ◆ Barraba, ▲ Manilla, □ Nundle and ○ Wagga Wagga, and (b) Δ Carcoar, ■ Maindample, ● Ruffy, ○ Vasey, and ◊ Esperance. Bars indicate the SE of observations.

Figure 6. Mean monthly surface runoff predicted by the SGS model over a 31-year period for ◆ Barraba, Δ Carcoar, □ Wagga Wagga, ■ Maindample, ○ Vasey, and ● Albany.

Table 1. Information on the SGS National Experiment treatments relevant to this paper

Site	Treatment description	Pasture type	Stocking method	P rate (kg P/ha.year) 1998-2000
Barraba	Control	Native	Continuous 4 sheep/ha	0
	Medium	Native	Rotational 4 sheep/ha	0
	High	Native + sub clover	Continuous 8 sheep/ha	7.3
Manilla	Control	Native	Continuous 3.1 sheep/ha	0
	Medium	Native	Rotational 3.1 sheep/ha	0
	High	Native + sub clover	Continuous 9.2 sheep/ha	11
Nundle	Control	phalaris	Continuous 6.1 sheep/ha	11
	High	phalaris	Continuous 12.3 sheep/ha	11
Carcoar	Control	Native/naturalised species	Continuous	0
	High	Sown introduced species	Flexible rotation	7.3
Wagga Wagga	Control	Naturalised mixed native pasture	Grazed within herbage mass limits	4.4
	High	Sown phalaris/annual legume pasture	Grazed within herbage mass limits	12.6
Maindample	Control	Naturalised pasture	Set stocked	5.5
	Medium	phalaris/subclover pasture	Set stocked	11
	High	phalaris/subclover pasture	Set stocked	22
Ruffy	Control	Naturalised pasture	Set stocked	4.5
	Medium	Cocksfoot/subclover pasture	Set stocked	9
	High	Cocksfoot/subclover pasture	Set stocked	27
Vasey	Control	Naturalised pasture,	Set stocked	8
	Medium	phalaris/subclover pasture	Set stocked	5.3
	High	phalaris/subclover pasture	Rotational	28
Esperance	Annual	Subclover	Set stocked winter spring only	9
	Kikuyu	Kikuyu/subclover	Set stocked summer-autumn only	9
Albany	Annual	Annual based pasture	Continuous	12.3
	Kikuyu	Kikuyu based pasture	Continuous	12.3

Table 2. Soil test values for P, S and K (0-10 cm depth) in spring 2000 and derived indices of availability for plant growth

Site	Treatment description	Bray P (mg/kg)	Colwell P (mg/kg)	Olsen P (mg/kg)	P-index [A]	Blair S (mg/kg)	S index [A]	Skene K (mg/kg)	K-index [A]
Barraba	Control	34	59	26	0.99	2	**0.41**	367	1.00
	High	38	66	30	1.00	9	0.96	383	1.00
Manilla	Control	13	25	11	0.86	2	**0.41**	440	1.00
	High	12	24	11	**0.85**	8	0.93	457	1.00
Nundle	Control	15	27	10	**0.84**	16	1.00	190	0.98
	High	17	30	11	**0.86**	18	1.00	307	1.00
Carcoar*	Control	5	*14*	*5*	**0.59**	5	0.83	126	0.97
	High	14	*24*	*19*	0.97	5	**0.83**	103	0.95
Wagga Wagga	Control	7	15	5	**0.59**	10	0.97	310	1.00
	High	34	41	20	0.97	26	1.00	250	1.00
Maindample	Control	5	14	6	**0.65**	8	0.94	100	0.88
	Medium	10	18	8	**0.76**	9	0.95	115	0.91
	High	22	38	16	**0.94**	13	0.99	110	0.90
Ruffy	Control	7	14	7	**0.68**	8	0.94	125	0.98
	Medium	19	30	13	0.90	6	**0.88**	275	1.00
	High	25	31	14	0.92	7	**0.90**	175	0.99
Vasey	Control	*9*	*16*	7	**0.71**	11	0.98	149	0.97
	Medium	*9*	*17*	7	**0.73**	7	0.92	109	0.93
	High	25	43	19	0.96	11	0.98	143	0.97
Esperance	Annual	5	8	6	**0.62**	5	0.80	53	0.82
	Kikuyu	4	20	12	0.88	4	**0.78**	100	0.96
Albany	Annual	18	19	10	**0.83**	7	0.92	123	0.91
	Kikuyu	42	69	27	0.99	27	1.00	320	1.00

Values in italics calculated by equations (1), (2), (3) or (4)

[A] P index calculated from equation (5), S index from equation (6) and K index from equation (7). Each index is considered to be non-limiting when the value is >0.95. The first limiting nutrient is shown in bold.

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Table 3. Carrying capacity, pasture legume content, averaged over 1998-2000, and the benchmark legume percentage required to balance N exports in wool and meat

Site	Treatment description	Carrying capacity (DSE/ha)	Increase in carrying capacity [A] (%)	Legume content (%)	Increase in legume content [A] (%)	Benchmark legume content [B] (%)
Barraba	Control	3.3		1.5		*4.9*
	Medium	5.9	79	0.6	-60	11.4
	High	10.4	215	5.5	267	*4.9*
Manilla	Control	3.4		0.9		*4.9*
	Medium	4.3	26	0.7	-22	6.1
	High	8.0	135	6.9	667	*4.9*
Nundle	Control	13.1		5.8		*4.9*
	High	15.5	18	18.0	210	*4.9*
Carcoar [C]	Control	7.0		3.6		7.7
	High	9.7	39	5.0	39	6.6
Wagga Wagga	Control	4.3		21.9		3.9
	High	7.7	79	17.0	-22	4.2
Maindample	Control	12.9		5.5		*7.8*
	Medium	17.4	35	13.6	147	*7.8*
	High	20.9	62	11.6	111	*7.8*
Ruffy	Control	8.8		6.4		*7.8*
	Medium	10.7	22	4.5	-30	*7.8*
	High	17.8	102	6.2	-3	*7.8*
Vasey	Control	8.2		6.3		4.1
	Medium	17.3	111	31.0	392	9.2
	High	24.0	193	15.3	143	11.1
Esperance [D]	Annual			34.1		*7.8*
	Kikuyu			17.1	-50	*7.8*
Albany	Annual	13.1		38.2		4.7
	Kikuyu	19.2	47	26.1	-32	6.8

[A] Calculated for each Site as 100*(value for treatment)/(value for control)-100
[B] Sites and treatments where *G* was calculated using Equation (9) are shown in italics.
[C] 1999 to 2001
[D] 1997 and 1998 only

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Table 4. Mineral N (kg/ha) in the soil profile (0-100 cm).

Site	Treatment	Month of sampling in 2001	Mineral N 0-100 cm (kg/ha)	NO_3^-N proportion of mineral N (%)
Barraba	Control	Nov.	23	9
	High	Nov.	25	44
Manilla	Control	Nov.	41	24
	High	Nov.	27	22
Nundle	Control	Oct.	21	24
	High	Oct.	27	26
Carcoar	Control	Dec.	55	22
	High	Dec.	43	21
Wagga Wagga	Control	Dec.	27	7
	High	Dec.	47	43
Maindample	Control	Apr.	102	78
	Medium	Apr.	125	59
	High	Apr.	138	84
Ruffy	Control	Apr.	42	62
	Medium	Apr.	113	84
	High	Apr.	84	77
Vasey	Medium	Oct.	105	37
	High	Oct.	55	38
Esperance	Kikuyu[A]	Dec.	31	23

A Esperance annual not shown because sampling was only to 75 cm.

Table 5. Soil properties and estimated rates of soil pH change (0-10 cm) for acidification rates estimated from measured carrying capacities (Table 3) and simulated nitrate leaching rates (Fig 1).

Site	Texture	Treatment	pH_{CaCl2}	Bulk density ($10^3 kg/m^3$)	pHBC (cmol H^+/kg)	Acidification rate (kmol H^+/ ha.yr)	N cycle acidification as percentage of total	Time to change pH by 1 unit (yr)	Time to acidify to pH 4.2 ($CaCl_2$) (yr)
Barraba	Clay loam	Control	*6*	*1.53*	*1.37*	0.20	2	103	186
		High	6	1.53	1.37	0.64	2	33	59
Manilla	Clay loam	Control	5.6	1.46	1.67	0.21	2	117	164
		High	5.6	1.46	2.05	0.49	2	61	85
Nundle	Loam	Control	4.6	1.34	2.11	0.80	1	35	14
		High	4.7	1.34	2.14	0.94	1	30	15
Carcoar	Sandy Loam	Control	4.7	1.36	3.03	4.46	91	9	5
		High	5.4	1.36	2.91	0.91	36	44	52
Wagga Wagga	Loam or clay loam	Control	4.6	1.54	2.6	0.96	73	42	17
		High	4.7	1.54	2.73	0.49	5	86	43
Maindample	Sandy loam	Control	4.2	1.34	3.4	4.60	83	10	0
		Medium	5.2	1.34	3.67	1.64	36	30	30
		High	5.3	1.34	3.74	1.85	32	27	30
Ruffy	Sandy clay loam	Control	4.2	1.41	4.18	4.36	88	14	0
		Medium	4.5	1.41	4.81	1.23	48	55	16
		High	4.5	1.41	5.29	1.66	36	45	13
Vasey	Sandy clay loam	Medium	4.7	1.35	2.58	1.55	33	23	11
		High	*4.7*	*1.35*	*2.58*	1.95	26	18	9
Esperance	Sand	Annual	*4.9*	*1.56*	*2.41*				
		Kikuyu	4.9	1.56	2.41				
Albany	Sand	Annual	*4.9*	*1.35*	*0.89*	4.75	83	3	2
		Kikuyu	4.9	1.35	0.89	1.21	5	10	7

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Table 6. Average flow-weighted total P and N concentrations (mg/L ± s. e.) in runoff water collected at northern (Barraba, Manilla and Nundle) and southern (Carcoar, Wagga Wagga, Maindample, Ruffy and Vasey) Sites, and the Australian stream water quality "trigger values", above which further investigation of risks is recommended (Anon 2000c)

Site	Treatment	Total P 1998	Total P 1999	Total P 2000	Total N 1998	Total N 1999	Total N 2000
Barraba	Control	0.59 [A]	1.24	1.99 [A]	1.60 [A]	2.52	2.64 [A]
	Medium	0.41 [A]	0.73 [A]	1.03 [A]	1.30 [A]	1.23 [A]	1.37 [A]
	High	-	-	1.36 [A]	-	-	1.41 [A]
Manilla	Control	0.19 [A]	-	0.47 [A]	0.82 [A]	-	2.02 [A]
	Medium	0.45 [A]	-	0.33 [A]	0.70 [A]	-	1.39 [A]
Nundle	Control	0.15 [A]	-	0.64 [A]	2.00 [A]	-	2.26 [A]
	High	0.15	-	0.45	-	-	10.44
Carcoar [B]	Control			0.22±0.06			2.51±0.34
	High			0.56±0.15			4.47±0.52
Wagga Wagga [C]	Control		0.24			1.8	
	High		1.0			2.3	
Maindample	Control	0.32±0.085	0.25±0.02	0.32±0.01	2.65±0.25	2.45±0.24	4.00±0.12
	Medium	0.31±0.033	0.18±0.007	0.12±0.01	5.71±0.34	2.80±0.11	2.93±0.11
	High	1.50±0.14	1.23±0.02	0.76	5.60±0.60	2.82±0.16	4.48
Ruffy	Control	0.28±0.020	0.23±0.01	0.34±0.01	2.85±0.15	3.17±0.14	10.83±0.96
	Medium	0.49±0.024	0.36±0.05	0.77±0.03	6.35±0.95	4.38±0.50	4.26±0.09
	High	0.76±0.15	-	0.26	6.83±1.48	-	1.61
Vasey	Medium	0.19±0.02	-	0.22±.03	2.40	-	2.88±0.33
runoff	High	0.34±0.06	-	0.38±0.07	2.32±0.27	-	4.12±0.44
Australian water quality trigger levels [D]		NSW	0.050			0.600	
		Victoria	0.032			0.422	

[A] based on single flow event; - no flow event ; [B] Carcoar data were for 1 September 2001 to 31 August 2002; [C] Wagga data are median concentrations 1998-2000, not flow-weighted, and not separated according to years; [D] Anon. (2000c) for lowland rivers

NB Confidence intervals only calculated if 5 or more runoff events occurred in a year

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Table 7. Measured surface runoff (mm/yr) for some SGS NE sites and streamflow from nearby gauged watercourses, over the period 1998-2000

SGS NE Site	Surface flow (mm/yr) Plot with least flow	Surface flow (mm/yr) Plot with greatest flow	Streamflow (mm/yr)	Reference stream gauging station
Barraba	1	28	29	Manilla River at WoodsReef (419047) [A]
			31	Manilla River at BlackSprings (419053) [A]
Manilla	1	11	32	Manilla River at BraBri (419020) [A]
Nundle	1	14	197	Peel River at Taroona (419081) [A]
Carcoar[B]	2	26	19	Belubula River at Blayney (412105)[C]
Wagga Wagga	2	12	87	Kyeamba Creek at Book Book (410156) [D]
Maindample	84	158	105	Brankeet Creek at Ancona (405251) [E]
Ruffy	6	20	119	Hughes Creek at Tarcombe Rd (405228)[E]
Vasey runoff	1	45	20	Dundas River at Cavendish (238220B) [E]

[A] NSW Department of Land Water Conservation, Barwon Region, Tamworth NSW 2340

[B] September 2001 to August 2002

[C] NSW Department of Land and Water Conservation, Orange, NSW

[D] Garry Carr, NSW Department of Land and Water Conservation, Tumut, NSW

[E] Data source for Victorian streams Department of Natural Resources and Environment, www.vicwaterdata.net

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Appendix. List of acronyms and symbols used in this paper

Acronym or symbol	Meaning
A	acidification rate, 10^5 cmol H^+/ha.year
B	benchmark legume percentage
BD	bulk density, 10^3 m^3
$\%clay$	percentage clay
C	Carrying capacity, DSE/ha
ΔpH	change in pH
DSE	dry stock equivalent
E	N export in wool and meat, kg N/DSE.year
ECEC	effective cation exchange capacity
G	Herbage accumulation, t/ha.year
K_{av}	Available potassium, mg/kg
NE	National Experiment
N_{fix}	kg N fixed per tonne of legume above-ground growth
$[P]$	P concentration in surface runoff, mg/litre
P_{Bray}	Bray P, mg P/kg
$P_{Colwell}$	Colwell P, mg P/kg
PER	Phosphorus Enrichment Ratio
$pHBC$	pH buffering capacity, cmol H^+/kg.pH
P_{Olsen}	Olsen P, mg P/kg
S_{av}	Available sulfur, mg S/kg
SGS	Sustainable Grazing Systems
T	Time, years
U	Pasture utilization rate, kg eaten per kg grown
V	soil volume for 1 ha to 10 cm depth

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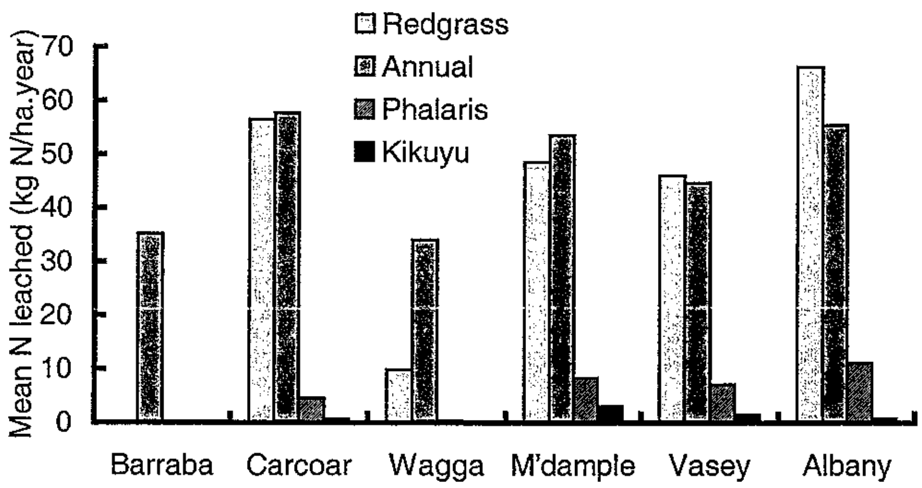

Fig. 1. Long-term nitrate leaching predicted by the SGS model.

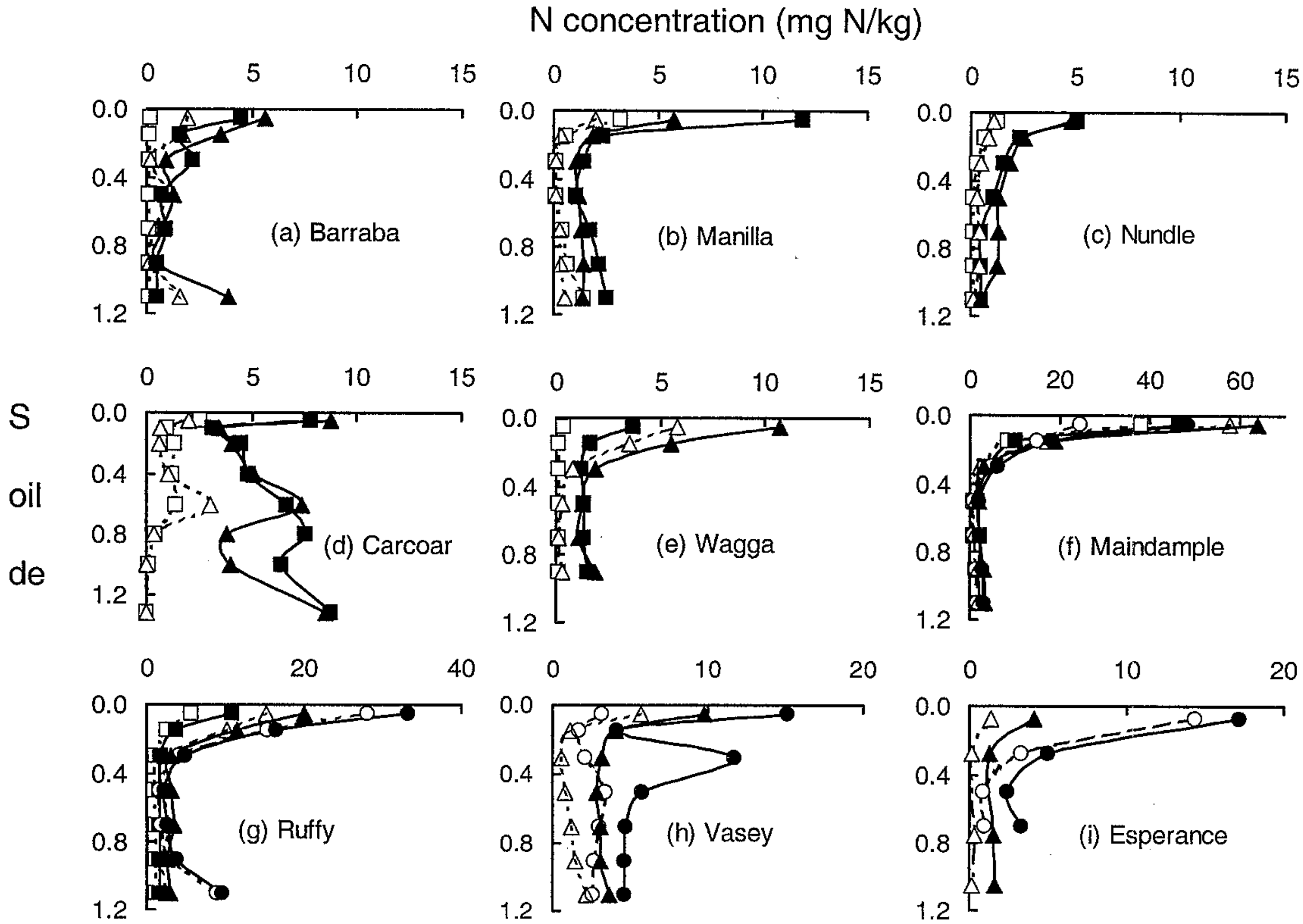
N concentration (mg N/kg)
S
oil
de
(a) Barraba
(b) Manilla
(c) Nundle
(d) Carcoar
(e) Wagga
(f) Maindample
(g) Ruffy
(h) Vasey
(i) Esperance

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Figure 2 Mineral N concentration in 2001 at (a) Barraba, (b) Manilla, (c) Nundle, (d) Carcoar, (e) Wagga Wagga, (f) Maindample, (g) Ruffy, and (h) Vasey, and (i) Esperance. Nitrate-N is represented as dashed lines with open symbols, and mineral N (nitrate + ammonium) as solid lines and filled symbols. □ ■ Control ○●Medium △▲ High treatment. For Esperance ○● Annual △▲ Kikuyu treatment.

[This Figure was prepared in Excel and composited in Powerpoint. When taken into Word, the y-axis label was changed from vertical to horizontal lettering.]

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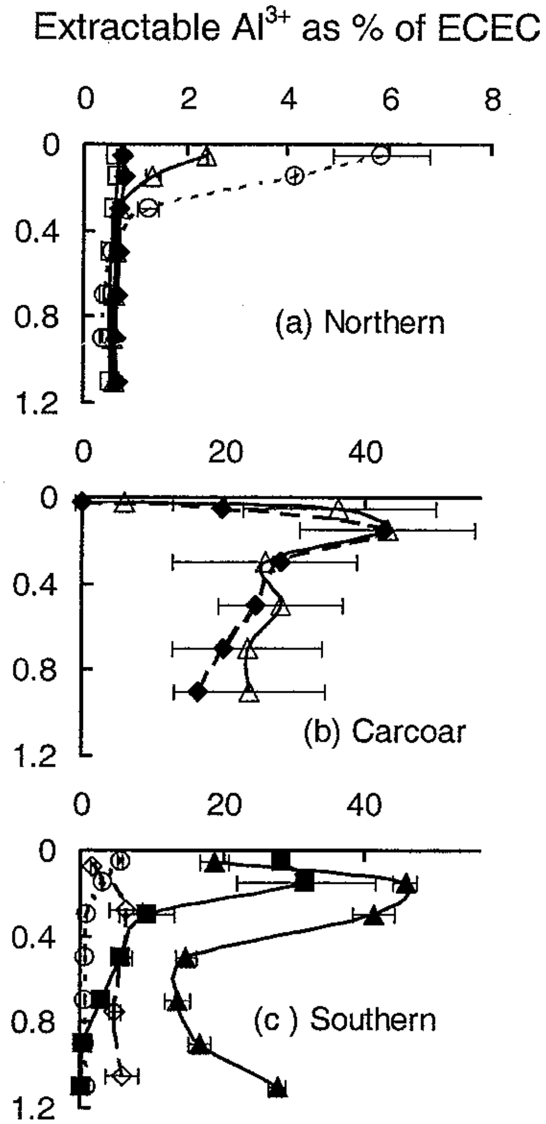

Fig. 3. Aluminium as a percentage of ECEC ± SE for (a) northern sites ◆ Barraba, ▲ Manilla, o Nundle (b) Carcoar ◆ limed (no SE) and ,Δ unlimed, and (c) southern sites ■ Maindample, ▲ Ruffy, ○ Vasey and ◊ Esperance.

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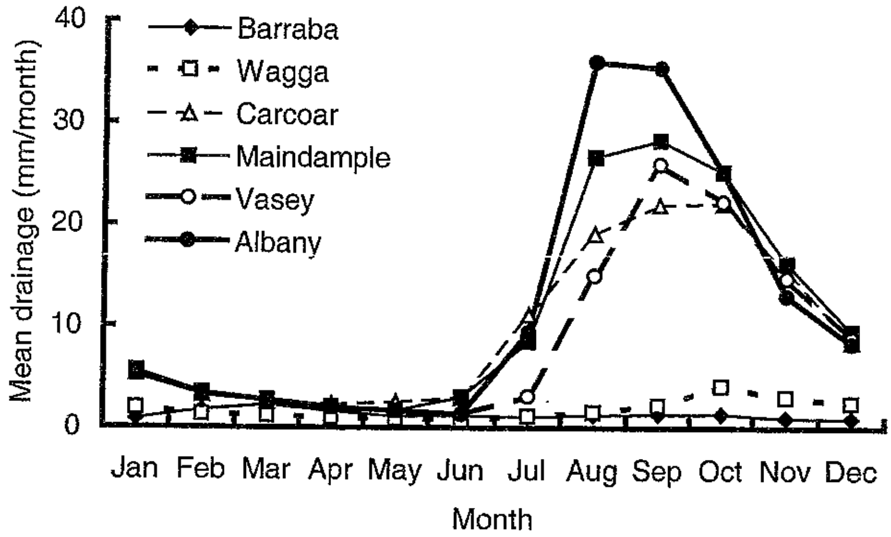

Figure 4. Monthly drainage predicted by the SGS model over a 31-year period for ◆ Barraba, Δ Carcoar, □ Wagga Wagga, ■ Maindample, ○ Vasey, and ● Albany.

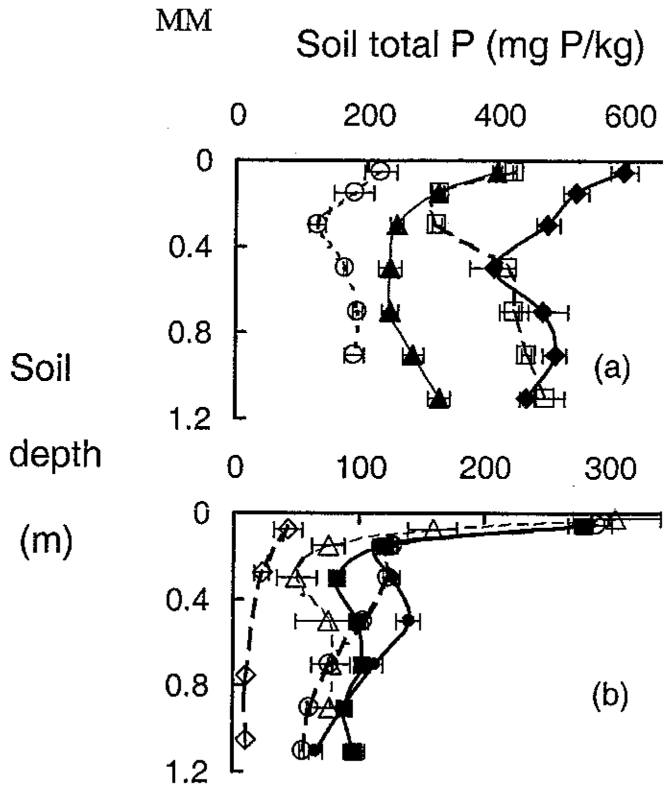

Figure 5. Total P in the soil profile for (a) ◆ Barraba, ▲ Manilla, □ Nundle and ○ Wagga Wagga, and (b) Δ Carcoar, ■ Maindample, ● Ruffy, ○ Vasey, and ◊ Esperance. Bars indicate the SE of observations.

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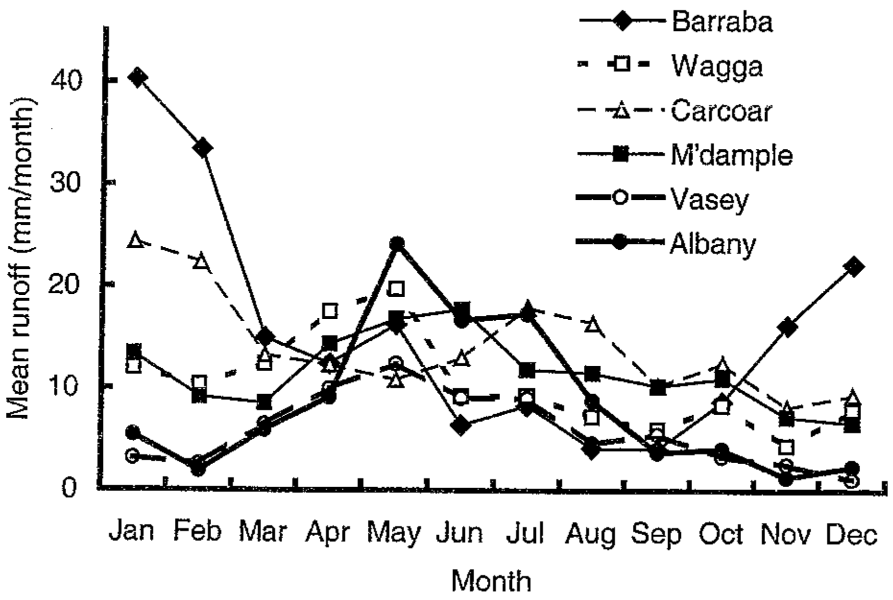

Figure 6. Mean monthly surface runoff predicted by the SGS model over a 31-year period for ◆ Barraba, △ Carcoar, □ Wagga Wagga, ■ Maindample, ○ Vasey, and ● Albany.