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Water use and soil acidification by pure legume pastures

Morelamb Environmental Component

Abstract

As part of a field experiment assessing the value of special-purpose legume monocultures for lamb finishing, soil measurements were made to determine N build-up in the soil profile. Treatments included Arrowleaf clover, a late-maturing annual legume, pure subterranean clover, and a perennial ryegrass-subterranean clover mixture. After one growing season the pure legume pastures had significantly more nitrate in the upper part of the soil profile (0-0.6m) than the grass/clover mixture. After 3 and 4 growing seasons, there was significantly more nitrate to at least 1.2m. Simulations using the SGS Pasture Model showed that the risks of N leakage below the root zone are minimal in the first 2 years of a pure legume pasture, but increase in subsequent years. To minimise the risks of nitrate leaching and soil acidification, recommendations from this study are that these legume monocultures only be used for up to 2 years, followed by a crop or pasture that can use the soil N. These guidelines will enable producers to use pure legume pastures with confidence that nitrate leaching and acidification risks are minimal.

Executive Summary

The production component of this project (MS.004) has shown that lamb growth rates in southern Victoria during October and November on pure subterranean clover pastures were 20-30% greater than on a conventional perennial ryegrass-subterranean clover pasture. Furthermore, the period of lamb weight gain could be extended until mid January through pure stands of the late-maturing annual legume Arrowleaf clover. The benefits of higher legume content do, however, come with a greater risk to the environment through nitrate leakage into groundwater, and soil acidification. To investigate the potential environmental cost of pure legume pastures, and recommend ways of ameliorating these risks, a study was conducted to measure soil nitrogen and water use by pure legume pastures.

Measurements were conducted in (i) a perennial ryegrass subterranean clover mixture, (ii) pure subterranean clover and (iii) pure Arrowleaf clover. Nitrate-N was measured to a depth of 1.2m in the autumn prior to imposition of treatments, then after 1, 3 and 4 growing seasons. Soil moisture was measured using a neutron probe, supplemented with data from the soil cores taken in autumn. The SGS Pasture Model was used to estimate leakage of water and nitrate below the root zone.

After one growing season the pure legume pastures had significantly more nitrate in the upper part of the soil profile (0-0.6 m) than the grass/clover mixture. After 3 and 4 growing seasons, there was significantly more nitrate to at least 1.2m. Nitrate levels were greatest for Arrowleaf clover, followed by subterranean clover. This was attributed to Arrowleaf clover not responding to rain in late summer and early autumn, whereas subterranean clover germinated and was able to take up some mineral N.

Soil measurements showed that a good stand of Arrowleaf clover was as effective as the grass/clover mixture at drying the soil in early summer. However, Arrowleaf clover was on average less effective at drying the soil than the grass/clover mixture, and was equivalent to pure subterranean clover. Rainfall between mid January (when Arrowleaf clover matured) and the end of autumn was utilised by the grass/clover mixture, and the pure subterranean clover, but not in Arrowleaf clover. Consequently, in a year with substantial rain in February, the soil was significantly wetter at the end of autumn with Arrowleaf than the grass/clover mixture or pure subterranean clover. Wetter profiles at the end of autumn increase the risk of water and nitrate movement below the root zone during the following winter.

Simulations showed that there was minimal risk of N leaching in the first and second years of a pure legume pasture. This is because the N is in plant forms that are protected from leaching, or high in the soil profile where there is a high root density. However, third and subsequent years of pure legume pastures carry a risk of enhanced leaching should these years have high water movement. A recommendation from this study is that pure legume pastures only be grown for 2 years, after which a crop or grass/clover mixture should be planted to utilise the nitrogen.

This recommendation is incorporated into production-oriented brochures and information material from the production component of this study, and will be distributed by sales agents for Arrowleaf clover.

Contents

1 Background

1.1.1 Lamb finishing on legume-rich pastures

As part of an initiative by Meat and Livestock Australia, a research project was commenced that tested a range of pasture-based options for lamb finishing. This project was known as “Morelamb Quality Pastures” (MS.004). Fieldwork was undertaken near Hamilton in southern Victoria, where lamb growth rates on conventional perennial ryegrass-subterranean clover pastures normally continue only until early to mid December, when the pasture dries off and the quality is insufficient for lamb growth. Options considered were

- Conventional summer forage crops (on commercial properties)
- Choice feeding systems
- Arrowleaf clover

In the choice feeding systems, ewes and lambs were supplied with a choice of pure grass or pure clover. During the October-November period when both pasture growth and lamb growth is normally at its maximum, lamb growth was 20-30% greater than when offered a conventional perennial ryegrass-subterranean clover mixture. Growth rates were similar to those of lambs offered pure subterranean clover. The use of choice or pure subterranean clover pastures allows more effective use of the period of rapid weight gain.

Arrowleaf clover is an annual clover that retains greenness and quality until late January, if required. The variety tested in the production experiment was developed by the Tasmanian Institute of Agricultural Research, and was released commercially in 2005. It grows poorly in winter, and most of its growth occurs in late spring. Growth rates are low after conventional pastures dry off in early to mid December, but because it retains quality, the period of lamb growth can be extended another 4-6 weeks.

Pure legume pastures involve a higher level of environmental risk than where a perennial grass is present. Kemp *et al.* (2000) reviewed a series of experiments quantifying the long-term sustainability of pastures in southern Australia grazed by sheep, and concluded that a high proportion of perennial grass (>60%) was required to control groundwater recharge and minimise nitrate leaching. The environmental risks of pure legume pastures are firstly that the legume does not extract as much water from the soil profile, leading to high rates of recharge, and secondly that excessive nitrogen causes acidification of the topsoil and nitrate contamination of groundwater.

Because of the potentially significant gains through finishing lambs on pure legume pastures, an environmental study was conducted on the same site as the production experiment, to examine whether Arrowleaf clover would use more soil water than conventional perennial ryegrass-subterranean clover pastures, and in this way compensate for the increased nitrogen leakage risk through not having a perennial grass. The study was designed to provide guidelines for how long pure clover pastures could be used, and quantify trade-offs between production benefits and environmental costs.

2 Project Objectives

Objectives of the project were to:

1. Quantify the potential impact on groundwater recharge from short and long-season legume pastures, including a description of the dewatering potential and physical characteristics of the target species (eg rooting depth, growth habit) and soil characteristics.
2. Develop guidelines for rotating high-legume pastures with other land uses to ensure long-term environmental sustainability by estimating of the soil acidification rate under these treatments.
3. Determine the potential compensation or trade-off of soil N increase for reduction in recharge to the water table.

3 Methods

3.1 Field measurements

In April 2002 a 32-hectare area of land was fenced into 24 plots of 1 ha and 4 plots of 2 ha. Soil was a yellow chromosol derived from basalt (see the full soil description in Appendix 1). Prior to sowing, soil was sampled to a depth of 1.2 m, in increments of 0.1 m to a depth of 0.2 m, followed by 0.2 m increments. In each plot, 4 cores were taken along a transect, and each depth increment bulked to form a single sample for each plot-depth combination. Cores were taken using a trailer-mounted hydraulic corer, with an internal diameter of 40mm. These samples were dried to $40^{o}C$ and analysed for the nitrate and ammonium forms of nitrogen, and pH in water and calcium chloride.

Treatments were
1. Pure subterranean clover (Subclover)
2. Pure Arrowleaf clover (Arrowleaf)
3. A perennial ryegrass-subterranean clover mixture (Mix)
4. Pure perennial ryegrass
5. Pure Diffuse clover
6. Perennial ryegrass-subterranean clover choice, consisting of 1 ha of pure perennial ryegrass adjacent to 1 ha of pure subterranean clover
7. A combination of various pure pasture species within a 1ha area

Only treatments 1 to 3 were applied consistently through the 4 years of the experiment. Pastures were maintained pure by a combination of resowing, grazing, and herbicides. In the 2005 growing season, Arrowleaf clover was oversown into the pure perennial ryegrass pasture to form a mixture.

In an effort to obtain more even growth of Arrowleaf clover, all plots were limed with 5 tonnes/ha of lime in April 2005.

Further soil cores were taken to a depth of 1.2m along the same transect of treatments 1-3 in March 2003, May 2005 and April 2006. These samples were dried to 40C and moisture content determined, then analysed for nitrate and ammonium. Data on moisture content were recorded for the samples taken in May 2005 and April 2006. The final sampling was also analysed for pH. Additional surface soil samples (0-0.1m) were taken monthly between April 2005 and April 2006 to monitor changes in nitrate and ammonium concentration and for pH on 5 occasions.

Neutron access tubes were installed to a depth of 1.8m during the March 2003 sampling on treatments 1 to 3 to measure soil water relations. Soil moisture was measured using the neutron probe in September and December in 2003 and 2004, then every 1-3 months until April 2006. Readings were more frequent between September (when the soil profile was full) and January (when Arrowleaf clover dried off). Reading depths were 0.15m, 0.3m, 0.5m, 0.9m, 1.3m and 1.7m. It is not feasible to measure soil moisture in the 0-0.1m horizon using the neutron probe, and this layer was instead measured opportunistically from surface soil samples collected for nitrogen determination.

A calibration relationship between neutron counts and soil moisture was obtained for 4 access tubes in May and October 2005. Field capacity was defined as maximum soil moisture recorded in any one tube. The soil water deficit, defined as the amount of water required to return the soil to field capacity, was calculated for each soil moisture reading, as described by White *et al.* (2003).

Soil moisture, mineral N and pH data were analysed by analysis of variance using Genstat 8. Separate analyses were conducted for each sampling time and depth. Pasture growth for each plot and growing season was used as a covariate, to allow for poor growth in some Arrowleaf plots.

3.2 Modelling

The SGS pasture model of Johnson *et al.* (2003) (version 3.5.7, build 3) was obtained from its developer, Dr Ian Johnson and used to simulate the growth of pure subterranean clover, pure Arrowleaf clover, and pure perennial ryegrass. The model does not simulate the growth of a mixed pasture. To supply nitrogen to the perennial ryegrass, 150 kg N/ha.year was applied in 3 applications during the winter-spring period. Growth parameters for Arrowleaf clover were developed by Stuart Smith of the Department of Primary Industries and Water Tasmania, Bob Reid of Tasmanian Global Seeds, Eric Hall of the Tasmanian Institute of Agricultural Research, and Sarah Campbell of the Department of Primary Industries and Water Tasmania. These staff had been involved in the development of the variety of Arrowleaf clover that was used in the Morelamb project.

Soil moisture parameters were developed from a soil pit located close to the centre of the research site, and soil samples that were taken adjacent to it at times of minimum and maximum soil moisture (May and October 2005 respectively). Initial soil nitrate and ammonium levels for the simulations were based on the initial soil measurements taken in April 2002. Nitrogen transformation parameters were taken from a simulation developed by Richard Eckard (personal communication), and was based on a detailed field study of gaseous N transformationis. Weather data for rainfall, radiation, and maximum and minimum temperatures were taken from Hamilton DPI Centre, located 4 km east of the research site. Potential evapotranspiration was taken from the SILO data set (Jeffrey *et al.* 2001) for the Hamilton DPI site, and was calculated using the methods of Smith *et al.* (1992).

To estimate the rate at which the topsoil could be acidified through nitrate leaking below a depth of 0.1 m, the model was rerun using a rooting depth and soil depth of 0.1 m. Leakage of water below the topsoil (L, mm) was multiplied by the observed topsoil nitrate-N concentration (NO3, mg/kg), and divided by the amount of water contained in the top 0.1 m of the soil profile (S, mm), ie

$$L = \text{NO3} \times \text{BD} / S$$

where BD is the bulk density (1.02 Mg/m3). This equation assumes that preferential movement of water does not occur in the topsoil. When leached, 14 kg of nitrate-N is equivalent to 1 kmol H^+ (10^5 cmol H^+), or 50 kg of lime (Slattery *et al.* 1991). A pH buffering (pHBC) value of 3.2 cmol H+/kg.pH unit was used, based on values on a similar soil on the Long-term Phosphate Experiment at Hamilton (McCaskill unpublished). The time (*T*, years) for pH to change (ΔpH) by 0.25 pH units was estimated by equation of Helyer and Porter (1989):

$$T = \Delta pH \times pHBC \times BD \times V/A$$

V the volume of soil in a hectare to a depth of 0.1 m, and *A* the acidification rate (cmol H^+/ha.year). These calculations were only undertaken for the 2005/06 growing season, because this was the only year with frequent topsoil nitrate data. The estimates should be considered maximum acidification rates, because they do not take account of plant uptake of cations from below the topsoil returning alkalinity to the surface.

4 Results and Discussion

4.1 Field measurements

4.1.1 Rainfall and soil moisture

Rainfall was well below the long-term mean in 2002 and 2005, but above average in 2003 and 2004 (Table 1). Dry conditions in 2002 allowed the Arrowleaf clover to establish evenly, whereas in 2003 and 2004 it died in parts of the site with poor drainage. Wet conditions during winter in 2003 and 2004 allowed the soil profile to recharge fully. Good summer rainfall was received in all years of the experiment, and it was particularly wet in February 2005.

Table 1. Rainfall (mm/month and mm/year) over the experimental period measured at the DPI Hamilton Centre, and the long-term mean (1971-2005).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2002	22	28	18	21	50	77	91	48	71	53	49	35	561
2003	44	56	63	29	23	110	76	94	72	93	27	40	728
2004	46	28	64	40	46	139	75	104	52	34	62	39	728
2005	35	68	15	25	25	64	37	79	54	51	52	36	541
2006	37	41	31	66	56								
Mean	35	27	40	50	59	73	79	83	78	69	53	44	690

Soil moisture data from the neutron probe showed the expected annual cycle of minimal deficits at the end of September, then becoming more strongly negative (drier) during December and January (Figure 1). Summer rainfall in 2005 caused a brief period of minimal deficits, after which the soil dried out during autumn before wetting during winter. The perennial ryegrass/subterranean clover mixture achieved the strongest soil water deficits, indicating that it dried out the soil most strongly. Deficits for Arrowleaf and pure subterranean clover were similar. However, one plot with a particularly strong Arrowleaf achieved a deficit that was similar to Mix. This plot had a steeper slope than most others, and its good drainage is likely to have contributed to the good performance of Arrowleaf clover.

There were small year-to-year treatment differences in the soil water deficit at the wettest time of the year. This is an artefact of the technique. Some neutron access tubes required replacement each season due to damage during cultural operations, and field capacity was defined as the wettest reading of any tube. For some tubes this was in 2003 or 2004, while for replacement tubes it was 2005, which was a slightly drier year.

Differences in soil moisture associated with the annual drying of the profile were evident at the 0.9m reading depth, but not at 1.3m (data not shown). The effective rooting depth of all species was assumed to be halfway between these reading depths, ie 1.1m.

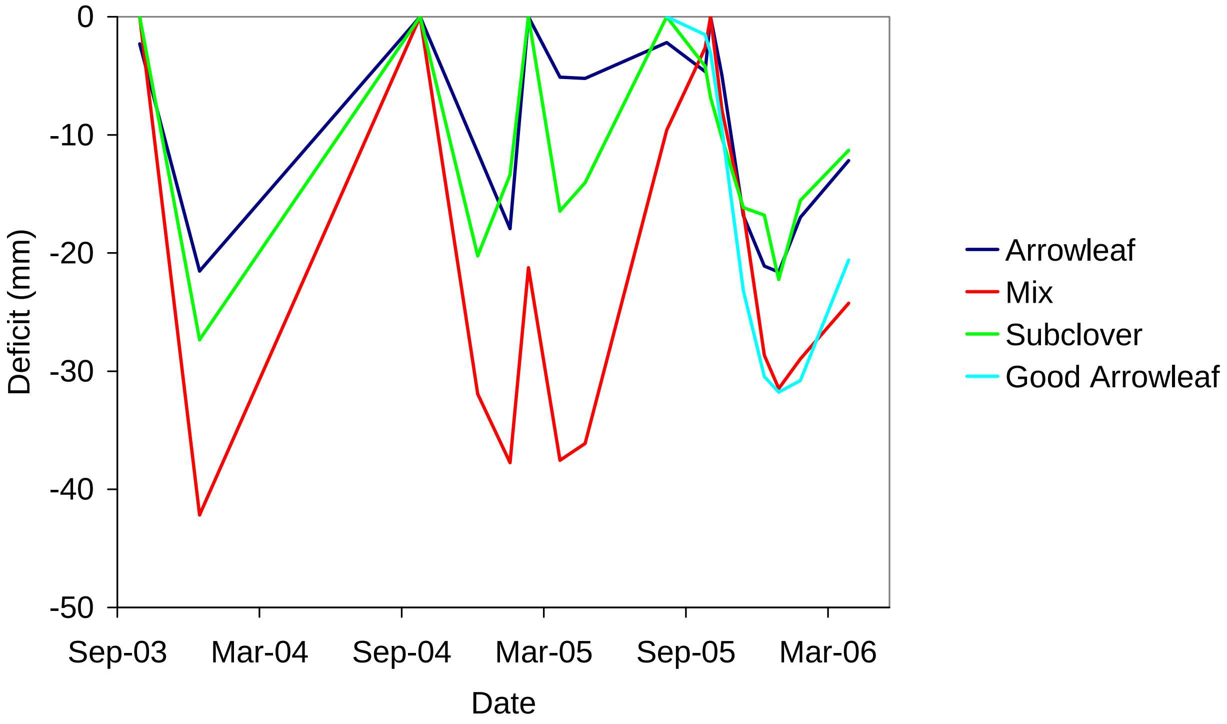


Figure 1. Soil water deficit (mm) 0.15 to 1.1 m, based on neutron probe data

Soil moisture data from coring in autumn 2005 showed that Mix and Subclover were the most effective at drying out the profile prior to winter, and that the soil was considerably wetter in the Arrowleaf treatment (Figure 2a). Arrowleaf clover was significantly wetter than the other treatments between 0.1 and 0.6m depth. The plot with the strongest stand of Arrowleaf was similar to Mix and Subclover. In autumn 2006, there were no significant differences in soil moisture (Figure 2b).

These data show no evidence that Arrowleaf clover was any more effective at drying the profile than Mix. It probably maintains its greenness in early summer through good internal control of moisture, and with the help of summer rainfall, rather than by drying the soil out more strongly. In an animal production system, Arrowleaf clover would be consumed by mid January while it has quality. This leaves little biomass to respond to further rainfall. Its seed would still be hard and not ready to germinate. However, perennial ryegrass is able to respond to summer rainfall, to deplete soil water stores before the end of autumn. Even subterranean clover germinated following February rainfall in

2004 and 2005, and was able to use moisture. In some years rain in February would cause a “false break”, but in both years the plants remained alive until winter.

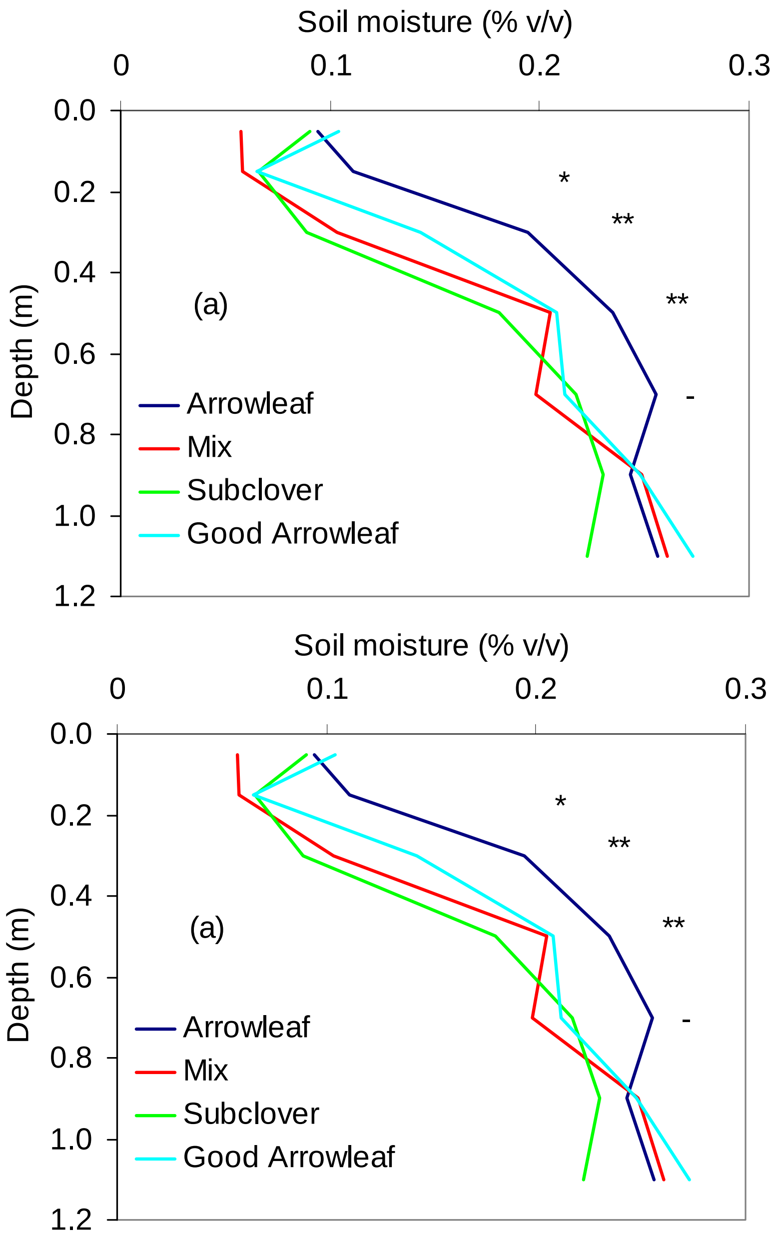


Figure 2. Soil moisture from coring on (a) 17 May 2005 and (b) 10 April 2006. Statistically significant differences within a depth are indicated as ** for P< 0.01, * for P < 0.05 and – for P < 0.1.

4.1.2 Soil nitrogen

At the first sampling, before treatments were imposed, there were no significant treatment differences in soil nitrate concentration (Figure 3a). However in 2003 after one growing season, both the Arrowleaf and Subclover treatments had significantly higher nitrate-N concentrations to a depth of 0.6m. In 2005 and 2006, Arrowleaf had significantly higher nitrate concentrations than Mix in the depth range 0.2 to 1.2m (Figure 3 c and d). Subclover was intermediate between Arrowleaf and Mix. These data clearly show a bulge, or zone of higher nitrate concentrations, starting high in the profile (2003), then moving deeper.

Soil ammonium data showed few significant treatment differences, and levels were low (<3 mg N/kg) below a depth of 0.4m. Of 21 possible depth-time comparisons after treatments were imposed, only 5% of treatment differences were significant at the 5% level. This level of detecting differences is no greater than would be expected with random effects. Ammonium leaches through the soil relatively slowly (at a rate similar to potassium), and unless converted to nitrate, does not represent the environmental risk of nitrate.

Topsoil nitrate concentrations during the 2005/06 growing season were highest on Arrowleaf, followed by Subclover and then Mix (Figure 4a). During winter, nitrate concentrations declined on subclover and Mix as the plants grew and took up mineral N. However, concentrations were steady then increased slightly on Arrowleaf. This would be because of its poor winter activity, with insufficient growth to take up the available mineral N.

During autumn 2006, nitrate concentrations increased on both Arrowleaf and Subclover. This would be because N-rich pasture residues were being mineralised at a faster rate than the plants could take it up.

There were few significant differences in topsoil ammonium concentrations (Figure 4b). Ammonium levels were between 20 and 40 mg N/kg during the relatively dry autumn of 2005, and then declined to a range of 10 to 20 mg N/kg for the remainder of the growing season.

Topsoil mineral N concentrations in areas where Arrowleaf clover was oversown into a perennial ryegrass pasture were similar to those in the Mix treatment (Figure 4). There were no statistically significant differences in nitrate or ammonium concentrations between strips oversown with Arrowleaf and those that were pure grass (data not shown).

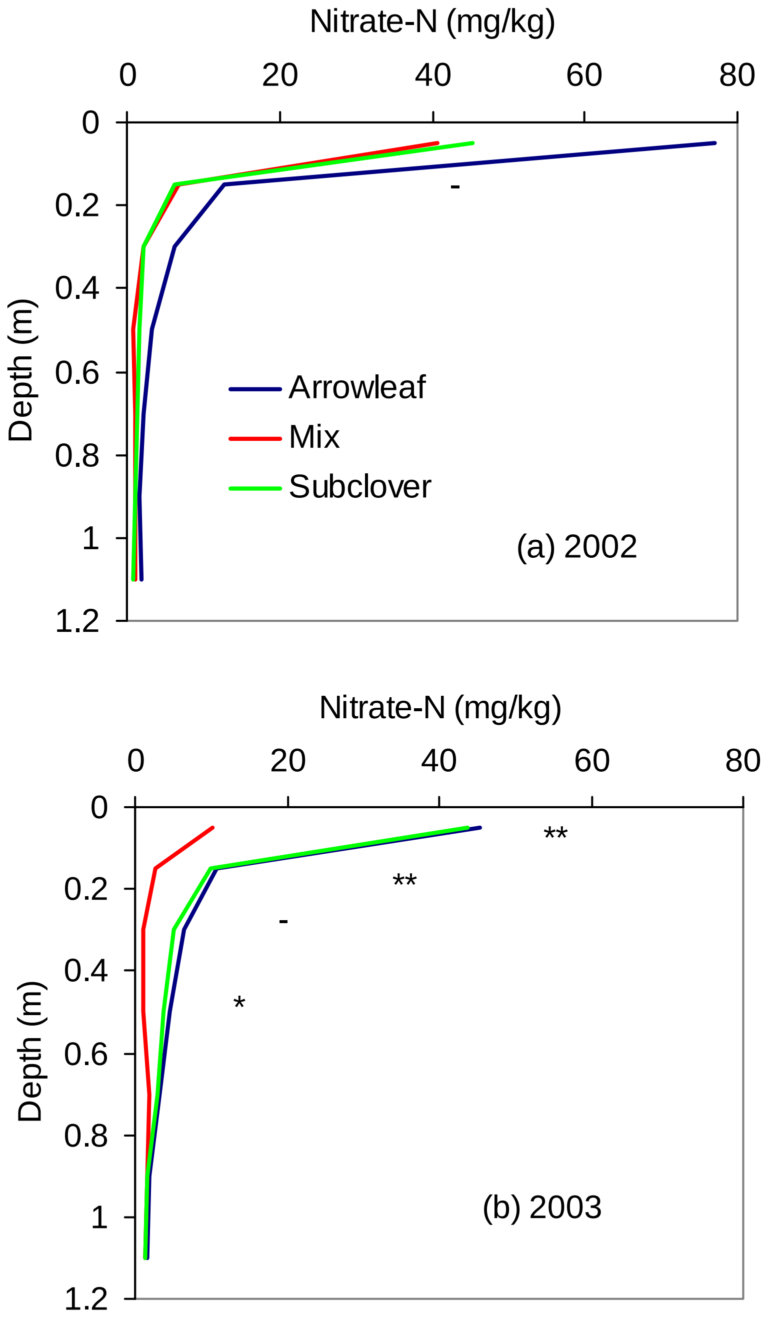


Figure 3. Soil nitrate concentration sampled in (a) autumn 2002 before treatments were imposed, and (b) autumn 2003. (See continuation of explanation on the next page)

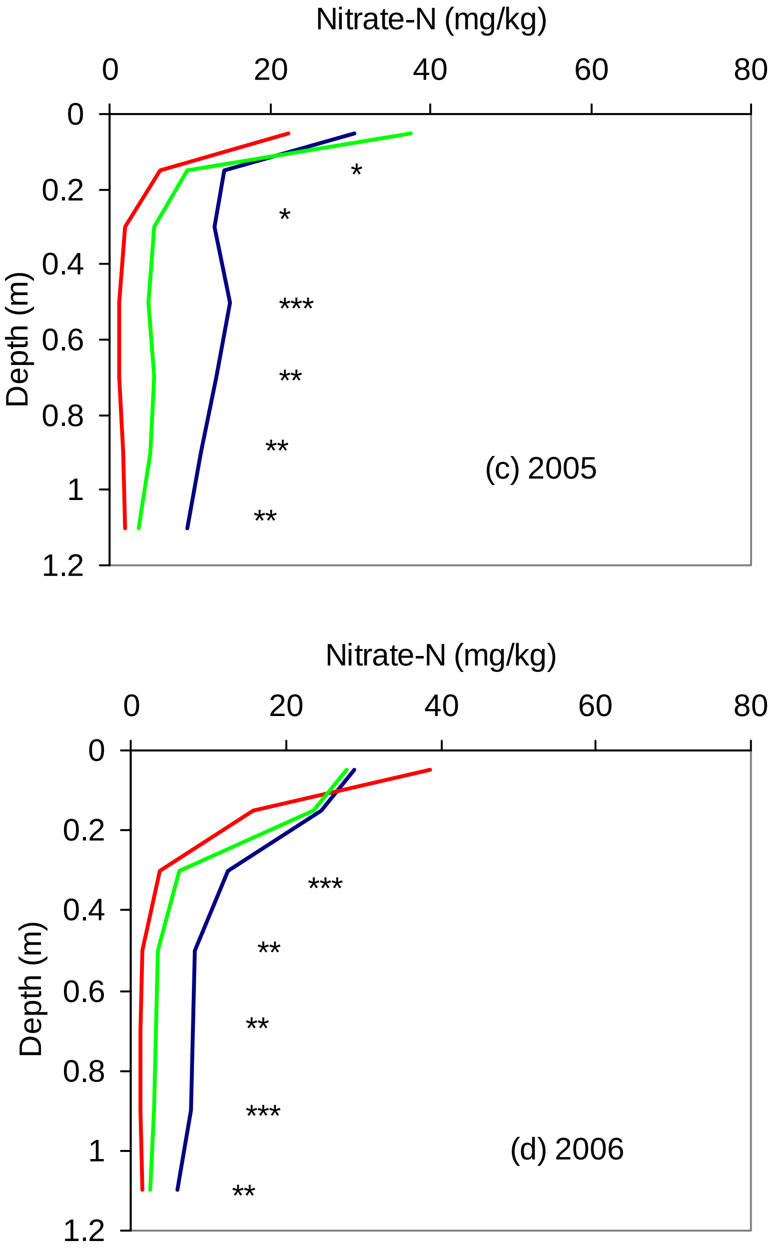


Figure 3 (continued). Soil nitrate concentration sampled in (c) autumn 2005 and (d) autumn 2006. Statistically significant differences within a depth are indicated as ** for P< 0.01, * for P < 0.05 and – for P < 0.1.

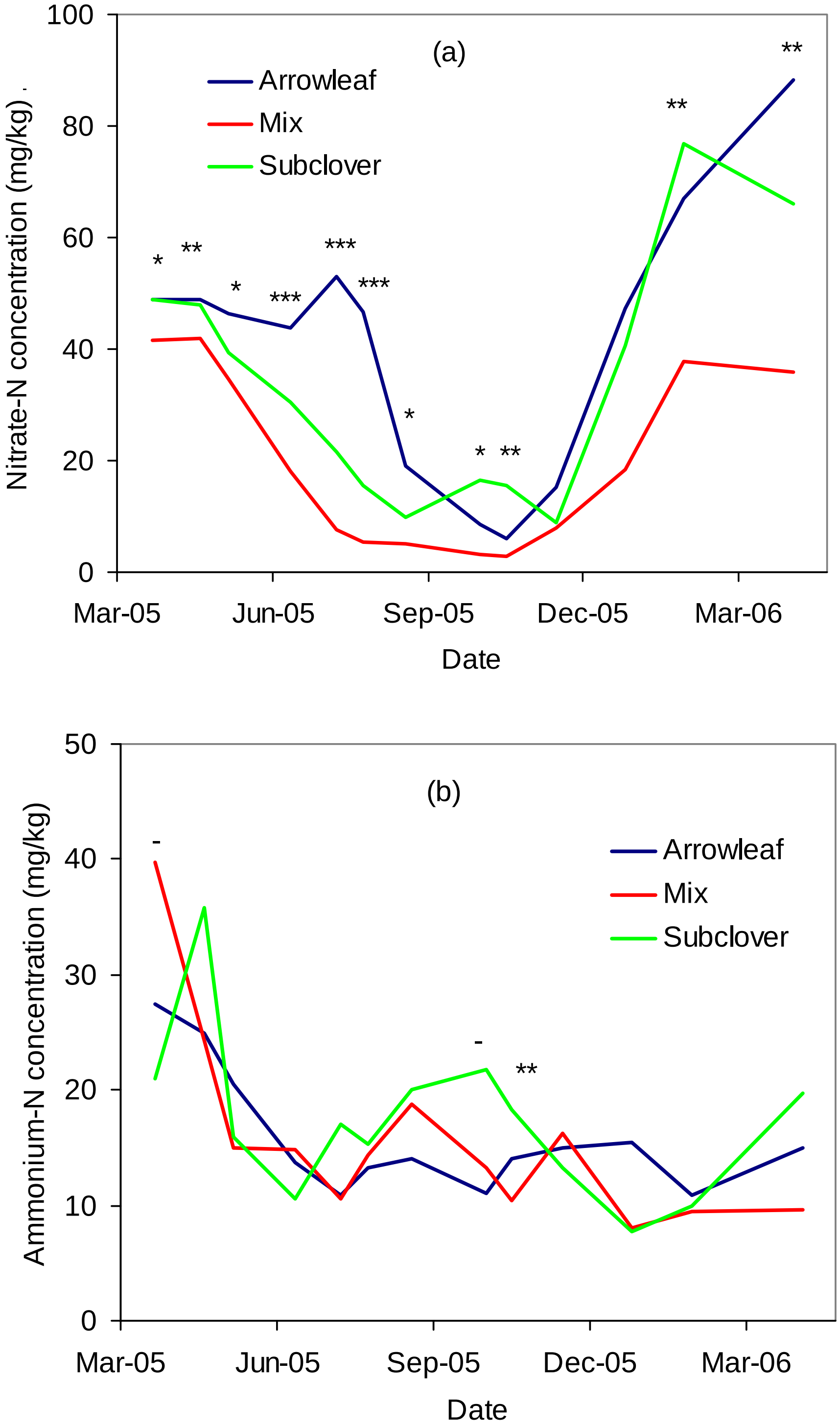
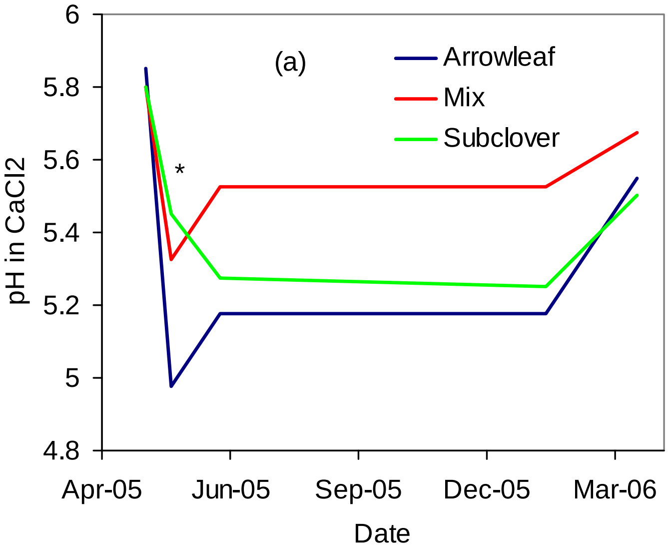


Figure 4. (a)Topsoil nitrate and (b) ammonium concentrations during 2005/06.

4.1.3 Soil pH

Soil pH after liming in April 2005 was virtually identical across treatments on 2 May 2005, but by the 19th of May the pH in both calcium chloride and water was significantly more acid on the Arrowleaf treatment. At subsequent samplings, differences were not statistically significant. Soil cores taken in autumn 2006 also showed no significant effects of treatment on soil pH at any of the depths sampled.



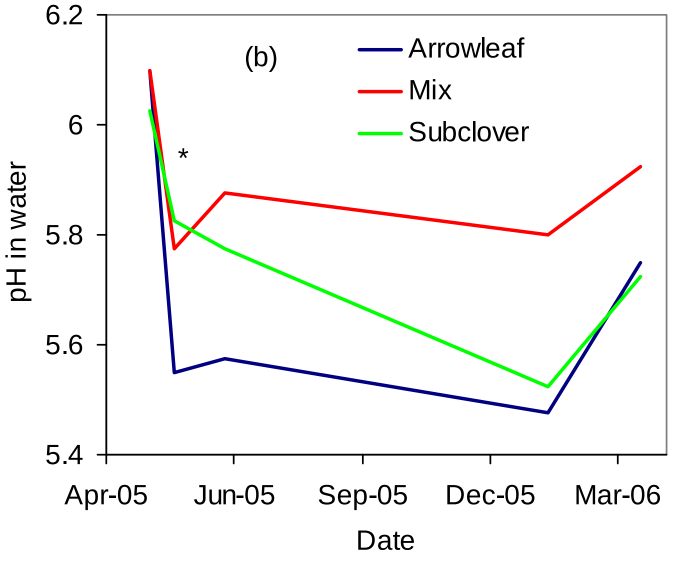


Figure 5. Topsoil pH in (a) calcium chloride and (b) water during the 2005/06 growing season. Statistically significant differences within a depth are indicated as, * for $P < 0.05$.

The more acid topsoil pH on Arrowleaf treatments in mid May 2005 was probably because nitrate from plant residues carried down cations, leaving the topsoil more acid. The effect would have been strongest on the Arrowleaf treatment, because it had residues rich in N, and there was little uptake of nitrate by the plant after the autumn break. The acidification was, however, relatively short-lived as other soil neutralising processes occurred, such as the dissolution of lime, and return of cations taken up by plants from deeper in the soil.

4.1.4 Modelling

The SGS Pasture Model showed large amounts of drainage from the Arrowleaf, followed by perennial ryegrass and then subterranean clover (Table 2). Arrowleaf clover had poor winter activity, and hence minimal winter transpiration, so large amounts of surplus water would drain through the profile. There was marginally more drainage under perennial ryegrass than subterranean clover. This is most likely to be because perennial ryegrass was dependent on fertiliser N, whereas subterranean clover could fix its own. If rain occurred on perennial ryegrass at a time when N fertiliser was not applied, its growth and transpiration would be minimal.

N leakage was greatest under Arrowleaf clover, whereas it was <2 kg/ha.year for subterranean clover and perennial ryegrass. Even for Arrowleaf clover, nitrate leakage was only modest (<15 kg N/ha.year) during the experimental period, and a wet year (weather data for 2001/02) was required to flush out nitrate that had moved deep into the root zone. Relatively little nitrate was flushed out from the subterranean clover and perennial ryegrass treatments, because these plants had better control of drainage, and were more effective at taking up nitrate from deeper in the root zone over the winter period.

The low N leaching rates of 0-2 kg N/ha.year from pure subterranean clover are from only one parameterisation of the model. In a sensitivity analysis, 2 variables – a leaching factor and a root distribution factor – were changed to favour greater leaching. Leakage of N increased to 0, 1, 23, 1 and 124 kg N/ha.year respectively for 2002/03, 2003/04, 2004/05, 2005/06 and 2001/02. In the second year of the simulation (2003/04), water movement was high but N leakage low. In the third year (2004/05), water movement was high and N leakage also high. In the fourth year (2005/06) there was no water movement and no N leakage. However in the fifth year (2001/02) high water movement combined with high soil stores of nitrate was responsible for a high rate of N leakage. High leakage of N therefore required more than 2 growing seasons of pure legume, and a wet year.

Gaseous losses from denitrification were small (0-2 kg N/ha.year). Volatilisation was modest (10-44 kg N/ha.year). These N loss pathways are expensive to measure, and the SGS Model was valuable in this study to quantify these aspects of the nitrogen cycle.

The SGS Model has been useful in running scenarios of pure legume pastures. Most of the N is fixed in mid to late spring, after the risk of leaching. The N is not released into the soil environment until the plant material is consumed. It is then returned as dung and urine, and the N stays close to the surface. In the second year, plants take up much of this N, and it is not until the end of the second year that a “bulge” of high nitrate concentration develops (Appendix 2, Figure A2.1). It is not until the third year that there is a risk of much nitrate-N moving below the root zone, when there is a bulge of first and second-year N in the lower part of the root zone, and a bulge of third-year N near the surface (Appendix 2, Figure A2.2). At this stage it is worthwhile to plant a vigorous non-legume to utilise the extra N. A further year of a pure legume pasture causes further N to accumulate in the third bulge (Appendix 2, Figure A2.3).

Table 2. Magnitude of N cycle processes for a subterranean clover pasture and a perennial ryegrass pasture, estimated from the SGS pasture Model for the years of the experiment (May 2002 to April 2006), followed by a wet year (weather data for May 2001 to April 2002).
Denit = denitrification; Volat = volatilisation

Arrowleaf clover							
Start	End	Rainfall	Drainage	Fixation	Leakage	Denit	Volat
		mm/year		kg N/ha.year			
1 May 02	30 Apr 03	666	263	373	0	0	15
1 May 03	30 Apr 04	713	305	118	5	1	10
1 May 04	30 Apr 05	694	182	177	15	1	29
1 May 05	30 Apr 06	573	0	155	0	0	29
1 May 01	30 Apr 02	775	315	134	183	2	8
Subterranean clover							
Start	End	Rainfall	Drainage	Fixation	Leakage	Denit	Volat
		mm/year		kg N/ha.year			
1 May 02	30 Apr 03	666	129	531	0	0	44
1 May 03	30 Apr 04	713	87	309	0	0	41
1 May 04	30 Apr 05	694	128	132	1	0	38
1 May 05	30 Apr 06	573	0	125	0	0	43
1 May 01	30 Apr 02	775	101	142	2	1	44
Perennial ryegrass							
Start	End	Rainfall	Drainage	Fixation	Leakage	Denit	Volat
		mm/year		kg N/ha.year			
1 May 02	30 Apr 03	666	145	0	0	0	19
1 May 03	30 Apr 04	713	87	0	0	0	33
1 May 04	30 Apr 05	694	135	0	1	1	29
1 May 05	30 Apr 06	573	0	0	0	1	25
1 May 01	30 Apr 02	775	114	0	2	2	32

Beyond 2 years of pure legume pasture only causes increased nitrate leaching if the years are dry with little water movement. Additional years of pure legume are, however, a risk factor for nitrate leaching and acidification. Another risk of pure legume pastures beyond the first 2 years is an increase in nitrogen-loving weeds such as capeweed and thistles. This risk is more easily seen by producers, and will help in the adoption of practices that sustain the soil resource.

A combination of a modelled topsoil water balance and observed topsoil nitrate-N concentrations showed that between 70 and 140 kg N/ha.year would have leaked below a depth of 0.1 m (Table 3). The highest rate of leaching was on Arrowleaf clover, followed by subclover and then the perennial ryegrass mixture. These N leakage rates are equivalent to a lime requirement of 0.25 to 0.5

tonne/ha, and in the absence of other processes would lead to a 1 unit change in pH every 3.3 to 6.5 years. The main counterbalancing process is the uptake of cations by plant roots from deeper in the soil, which returns alkalinity to the surface. However, if substantial water leaks below the root zone, rapid soil acidification of the topsoil could be expected. In the Arrowleaf simulation for 2001/02 (Table 2), a leakage of 183 kg N/ha.year was calculated. This is equivalent to a 1 unit change in pH every 2.5 years, if all the acidification occurred in the topsoil. Other treatments in Table 2 had N leakage rates of up to 2 kg N/ha.year, which is equivalent to a 1 unit pH change every 228 years. These calculations highlight the importance of plants taking up nitrate and associated cations from deep in the soil profile before they leach below the root zone.

Table 3. Maximum acidification rate of topsoil for 2005/06

	Arrowleaf	Mix	Subclover
Total N leached (kg N/ha.year)	139.4	70.4	116.0
Acidification rate (kmol H+/ha.year)	10.0	5.0	8.3
Lime required to neutralise this acidity (tonnes/ha.year)	0.50	0.25	0.41
Time for pH to change by 1 unit	3.3	6.5	3.9

5 Success in Achieving Objectives

5.1.1 Objective 1: Quantify the groundwater recharge

Achieved. Groundwater recharge was highest with the long-season legume pasture (Arrowleaf clover), because it had poor winter activity and did not respond to rainfall beyond its maturity time of late January. Recharge from Subclover and Mix was similar.

5.1.2 Objective 2: Develop rotation guidelines

Achieved. This objective of developing guidelines for rotating high-legume pastures with other land uses was achieved by both experimental measurements and modelling. Experimental measurements showed that after the first year of a pure legume pasture, nitrate-N was high in the profile where roots could readily extract it. By the third year, nitrate had moved lower in the soil profile, where the root density was low and water movement could easily move it below the root zone. Modelling showed that there were minimal risks of N leaching in the first 2 years of a pure legume pasture, but that the risks gradually increased in the third and subsequent years as nitrate-N built up deeper in the profile.

5.1.3 Objective 3: Determine nitrogen vs recharge trade-offs

Partially achieved. This study showed that there was no trade-off between soil nitrogen increase and reduction to the water table. Even the best stands of Arrowleaf clover used no more water than a perennial ryegrass-subterranean clover mixture. Furthermore, water use by Arrowleaf during summer was on average substantially less than the grass-clover mixture, and similar to pure subterranean clover. There was therefore no need to examine tradeoffs between water use and nitrogen leaching, because they are both poor.

6 Impact on Meat and Livestock Industry

The meat industry is under continued pressure to become more efficient without compromising the environment. The Morelamb production study has been instrumental in getting leading producers to use special-purpose pastures. The environmental component continues MLA's record of investigating both production and environmental aspects on the same sites and within the same projects. Recommendations from the environmental component are included within a brochure on production aspects of Arrowleaf clover and special-purpose pastures.

While this study has examined only 2 pure clover pastures, there is application to many other pastures with a high legume content. A concurrent project also conducted by the same team at DPI Hamilton, uses 2 other pastures with a high legume content. This project, Evergraze (funded by MLA, DPI and the CRC for Plant-based Management of Dryland Salinity), includes treatments of lucerne and subterranean clover/kikuyu. Following interim findings from the Morelamb study, the lucerne treatment has been modified to include a cereal oversown each winter to utilize N fixed by the clover, as well as boost winter growth and reduce nitrogen-loving weeds.

7 Conclusions and Recommendations

The Morelamb project extended current boundaries of both animal production, and the criteria that define a sustainable pasture system. While for most pastures a 60% perennial grass content is desirable to ensure soil moisture depletion before the end of autumn, and to take up mineral N before it leaches (Kemp *et al.* 2000), this study has shown that there are situations where much higher legume contents can be sustained for short term special purpose pastures. Two years of pure clover do not represent a leaching risk, but in subsequent years the risk gradually increases as N builds up deeper in the soil profile.

Of the 2 pure legume pastures tested here, subterranean clover was the easier one to manage, and carried fewer environmental risks. Selective herbicides are available to ensure stand purity, it responds to rain in late summer, and takes up mineral N early in the season.

Arrowleaf clover clearly needs a companion plant with winter activity, to take up N and minimise drainage. This would have the added benefit of providing feed in winter, which is the most limiting time of the year. In the last year of the experiment, Arrowleaf clover was oversown into perennial ryegrass, which did not increase the risk of N leaching. However, growth of Arrowleaf suffered through competition from the grass. Other options include a grass that can be sprayed out in spring, or spring sowing of Arrowleaf.

8 Acknowledgements

The author acknowledges funding for the first stage of this project (February to June 2003) from the DPI Meat Strategy, and for the second stage (November 2004 to December 2006) from both Meat and Livestock Australia, and DPI. Staff responsible for measurements of the project included Tim Jackson, Jane Jennings, Reto Zollinger, and Heather Ryan. Mark Imhof, Austen Brown and Darren Bennetts undertook the soil pit description. Brendan Cullen and Ian Johnson assisted with parameterising the SGS Model. Andrew Thompson initiated the production study, and was ably assisted by Andrew Kennedy and Jayne Holmes. These staff imposed the treatments that were measured in this study. We thank the Gubbins family for use of their land for the study.

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10 Appendices

10.1 Appendix 1. Soil description

Aust. Soil Class.: Bleached-Ferric (& Reticulate), Eutrophic, Yellow CHROMOSOL

General Landscape Description: Upper slope of low rise.
Site Description: Adjacent to CRC trial site.
Geology: Deeply weathered Tertiary basalt (approx. 4Ma).

Soil Profile Morphology:

Surface Soil

A1 0-10 cm Dark brown (10YR3/3); *fine sandy clay loam (slightly spongy);* weak coarse blocky, parting to moderate blocky structure; firm consistence (dry); ferruginous nodules (2-8 mm) common (20%); pH 6.3:

A2c 10-25 cm Dark yellowish brown (10YR4/4) (10YR6/4 dry); *fine sandy clay loam;* very many (50%) ferruginous nodules (2-15 mm); ferro-manganiferous (magnetic) nodules; pH 5.6:

Subsoil

B21c 25-35 cm Yellowish brown (10YR5/6); *light clay (subplastic)*; weak medium blocky, parting to moderate-strong medium to fine polyhedral structure; very firm consistence (moist) to strong consistence (dry); ferruginous nodules common (20%) (2-10 mm); pH 6.2:

B22 35-50 cm Reddish yellow (7.5YR6/8) with few dark red (2.5YR4/8) mottles; *light medium clay*; strong coarse to medium polyhedral structure; very firm consistence (moist) to strong consistence (dry); few (5%) ferruginous nodules; pH 6.5; gradual change to:

B23 50-100 cm Reddish yellow (7.5YR6/8) with many (50%) dark red (2.5YR4/8) mottles; *medium clay*; strong coarse to medium polyhedral, parting to fine polyhedral structure (shiny-faced peds); very firm consistence (moist); few ferruginous nodules (2-5 mm); pH 6.3; gradual change to:

B24 100-140+ cm Light yellowish brown (2.5Y6/4) with many dark red (2.5YR4/8) and light grey (10YR7/1) mottles (reticulated mottling); *medium clay*; strong medium to coarse polyhedral, parting to fine polyhedral structure (shiny-faced peds); with nests of lenticular structure; very firm consistence (dry); pH 6.2.

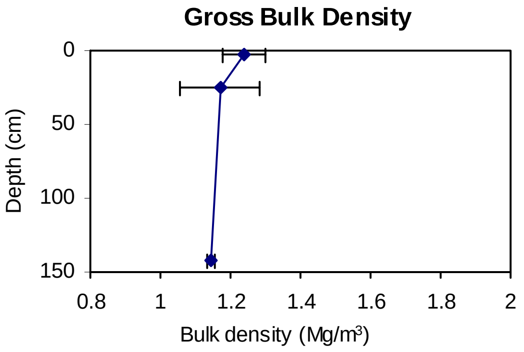
Key Profile Features

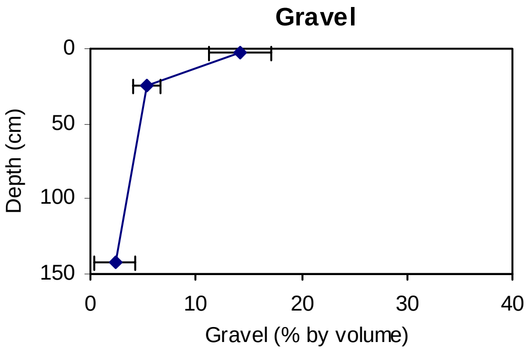
- ☐ Strong texture contrast between surface (A) horizons and subsoil (B) horizons.
- ☐ Many ferruginous nodules in subsurface (A2) horizon.

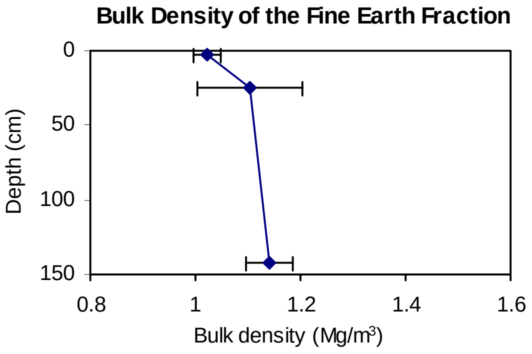
Key Profile Characteristics

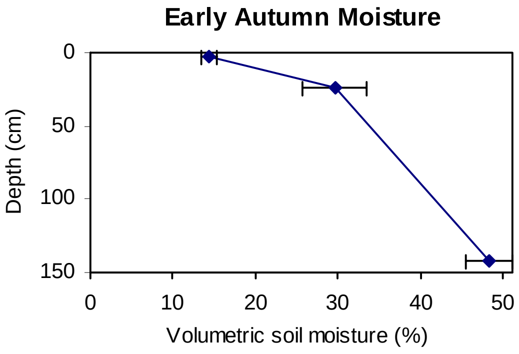
	pH	Salinity	Sodicity	Dispersion
Surface (A1 horizon)	Strongly Acid	Low	Non-Sodic	None
Subsoil (B21c horizon)	Slightly Acid	Very Low	Non-Sodic	None
Deeper subsoil (at 100-140+ cm)	Slightly Acid	Very Low	Marginally Sodic	None

Horizon	Horizon Depth (cm)	pH (water)	pH $CaCl_2$	EC dS/m	Exchangeable Cations meq/100g				Ex Al mg/kg	Ex Ac meq/100g	Field pF2.5	Wilting Point pF4.2	Gravel %	Coarse Sand (0.2-2.0mm)	Fine Sand (0.02-0.2mm)	Silt (0.002-0.02mm)	Clay (<0.002mm)
					Ca	Mg	K	Na									
A1	0-10	5.1	4.7	0.25	4.6	1.6	1.0	0.51	35	17	35.3	15.3	25	12	32.5	21.5	18.5
A2c	10-25	5.6	4.9	0.06	3.4	1.6	0.21	0.35	16	8.8	24.9	9.8	55	24	32	21.0	18.0
B21c	25-35	6.2	5.6	0.08	4.2	4	0.15	0.58	<10	9.7	33.1	22.4	22	8.5	19.0	11.0	57.0
B22	35-50	6.5	6.2	0.11	4.6	5.4	0.16	0.87		11	42.3	30.9	8	2.4	8	10.5	75.0
B23	50-100	6.3	6.1	0.13	4.1	5.7	0.12	1	<10	9.3	43.1	31.7	6	3.0	7.5	8.0	78.5
B24	100-140+	6.2	6.1	0.14	3.5	7.1	0.11	1.2	<10	9.0				2.5	9.5	12.5	75.0









Horizon	Horizon depth (cm)	Gross Bulk Density 105^{o}C (Mg/m^3)	Bulk Density Fine Earth 40^{o}C (Mg/m^3)	Gravel		Moisture 12 March 2003 (% vol.)
				% w/w	% vol.	
A1	0-5	1.24	1.02	30	14	14
B21c	22-27	1.17	1.10	12	5	30
B24	140-145	1.15	1.14	5	2	48

Notes:

1. The mean gravel density from 13 samples at the site was 2.62 ± 0.27 Mg/m^3. This mean value was used for all mass-volume conversions involving the gravel component.
2. Data points represent the mean of 4 replicates within each horizon, and error bars on graphs indicate the standard deviation for the 4 samples.

Management Considerations:

Surface (A) Horizons

- The surface soil (upper 10 cm) is strongly acid which indicates that aluminium and manganese toxicity may occur. The level of exchangeable aluminium measured at this site is not moderate (i.e. 35 mg/kg). A pH/aluminium test is, however, best performed from samples taken across the paddock and bulked together. Other factors also need to be considered before lime is recommended (e.g. pasture species grown, method of application, local trial responses, soil surface structure and likely cost/benefit).

Subsoil (B) Horizons

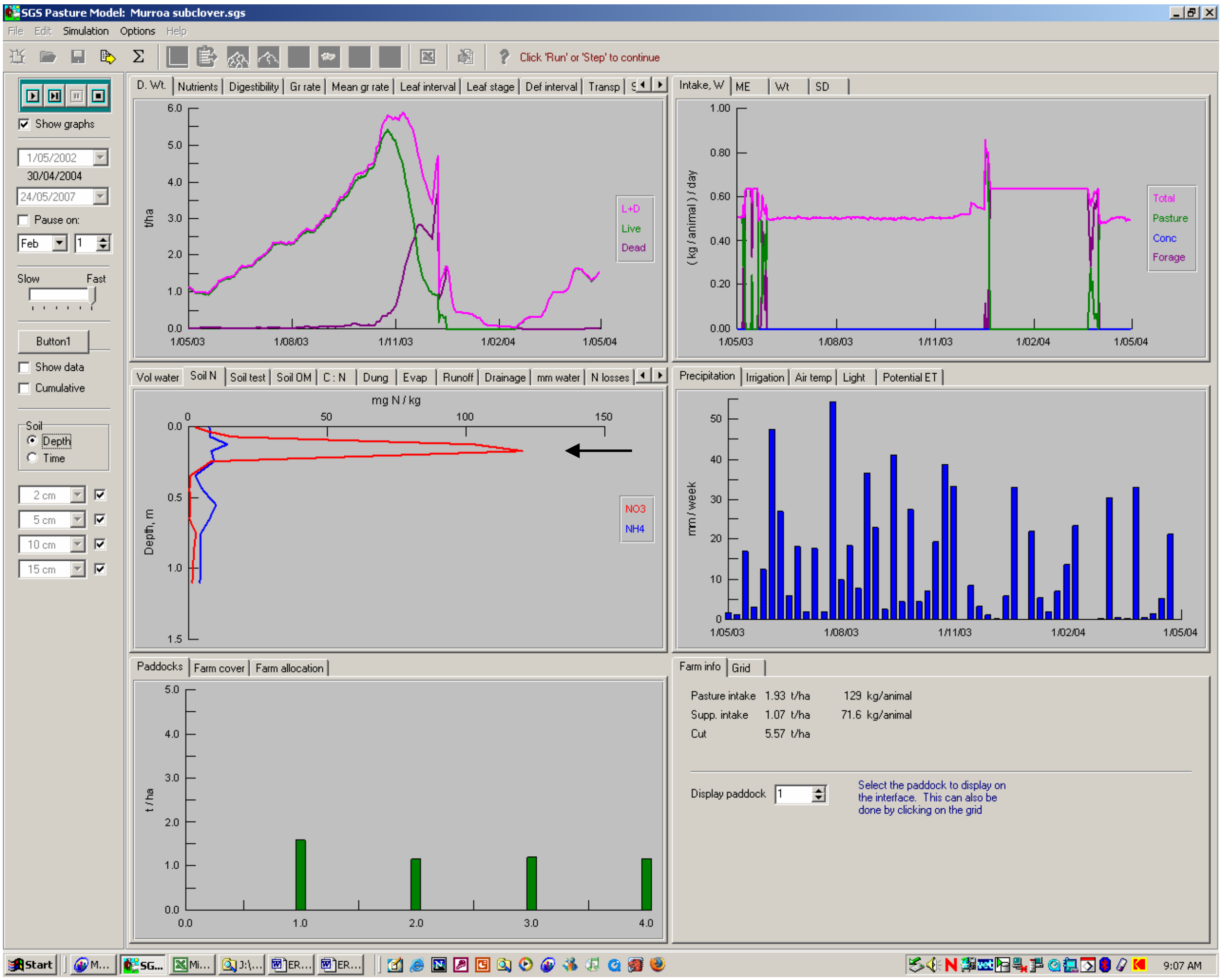
- The upper subsoil is non-sodic and well structured (parting to fine polyhedral aggregates). This will be conducive to root and water movement – although the strong texture contrast will provide some restrictions.

Notes:

- Profile described by Mark Imhof, Austin Brown, Darren Bennetts and Malcolm McCaskill - March 2003.
- Profile edited by: Mark Imhof, Angela Murphy, Malcolm McCaskill and Rachel Eats – February 2004.

10.2 Appendix 2. SGS Model output

Figure A2.1. Screen capture from the SGS Model after 2 years of a pure subterranean clover pasture, for 30 April 2004. Note the single bulge in soil nitrate (arrow). [In this simulation parameters were changed to enhance leaching.]



SGS Pasture Model: Murroa subclover.sgs

Click 'Run' or 'Step' to continue

☑ Show graphs

1/05/2002

30/04/2004

24/05/2007

☐ Pause on: Feb 1

☐ Show data

☐ Cumulative

Soil: ● Depth ○ Time

2 cm ☑

5 cm ☑

10 cm ☑

15 cm ☑

Pasture intake 1.93 t/ha 129 kg/animal

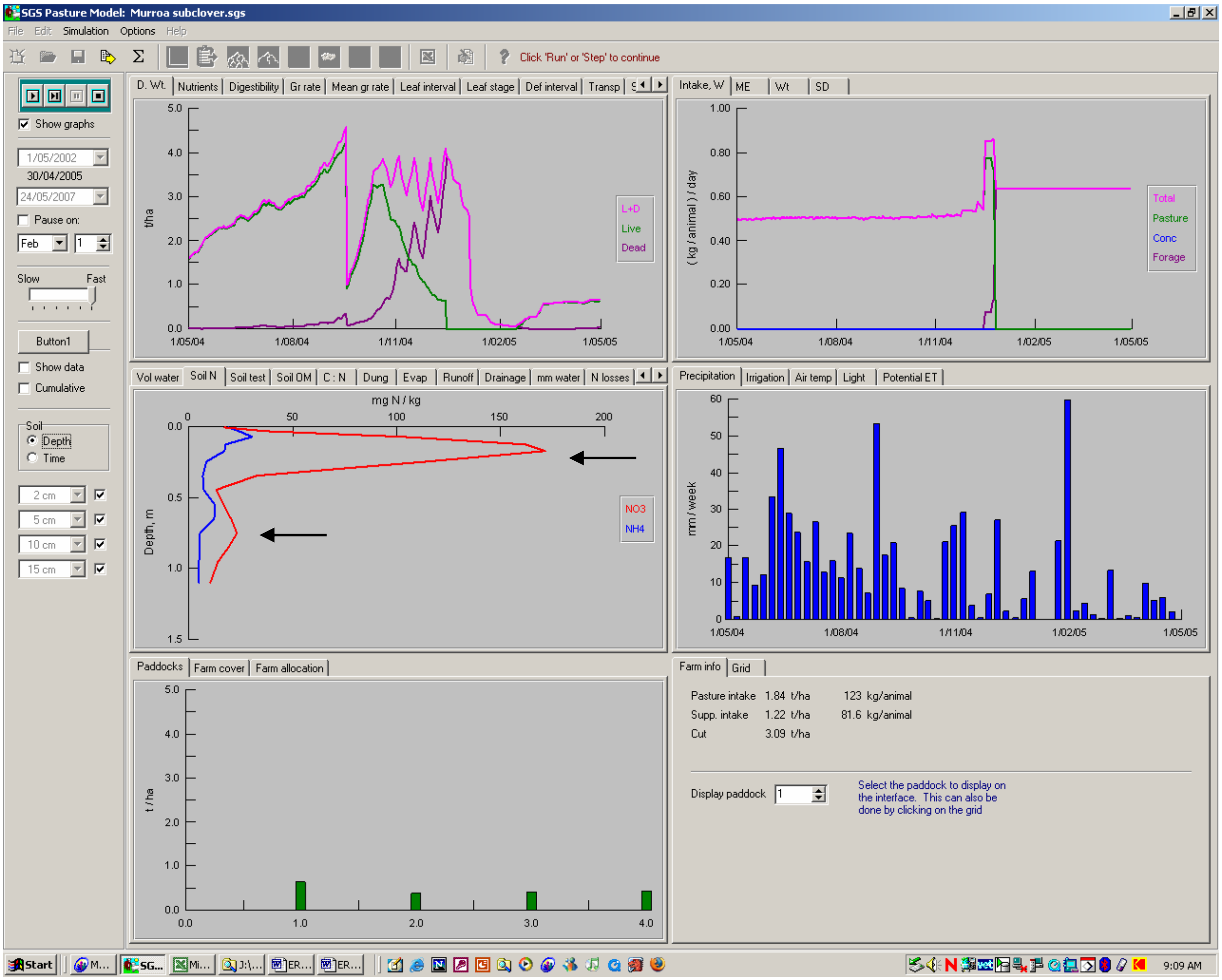
Supp. intake 1.07 t/ha 71.6 kg/animal

Cut 5.57 t/ha

Display paddock 1

Select the paddock to display on the interface. This can also be done by clicking on the grid

Figure A2.2. Screen capture from the SGS Model after 3 years of a pure subterranean clover pasture, for 30 April 2005. Note the two bulges in soil nitrate (arrows), the bottom one from N fixation in 2002 and 2003, the upper from fixation in 2004.



SGS Pasture Model: Murroa subclover.sgs

Click 'Run' or 'Step' to continue

☑ Show graphs

1/05/2002

30/04/2005

24/05/2007

☐ Pause on: Feb 1

☐ Show data

☐ Cumulative

Soil: ● Depth ○ Time

2 cm ☑

5 cm ☑

10 cm ☑

15 cm ☑

Pasture intake 1.84 t/ha 123 kg/animal

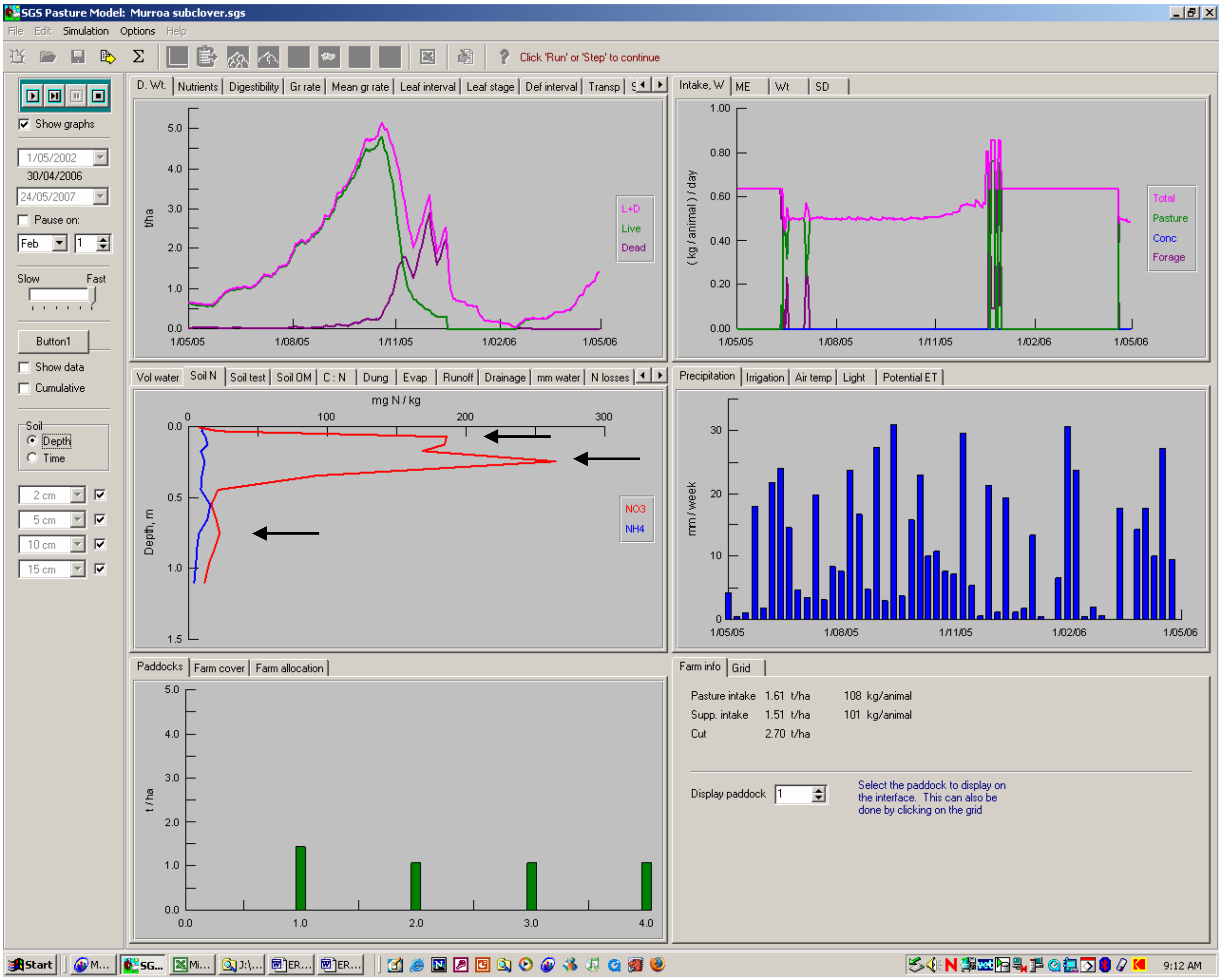
Supp. intake 1.22 t/ha 81.6 kg/animal

Cut 3.09 t/ha

Display paddock 1

Select the paddock to display on the interface. This can also be done by clicking on the grid

Figure A2.3. Screen capture from the SGS Model after 4 years of a pure subterranean clover pasture, for 30 April 2006. Note the three bulges in soil nitrate (arrows), the bottom one from N fixation in 2002 and 2003, the middle from fixation in 2004, and the upper from fixation in 2005.



SGS Pasture Model: Murroa subclover.sgs

Click 'Run' or 'Step' to continue

☑ Show graphs

1/05/2002

30/04/2006

24/05/2007

☐ Pause on: Feb 1

☐ Show data

☐ Cumulative

Soil: ● Depth ○ Time

2 cm ☑

5 cm ☑

10 cm ☑

15 cm ☑

Farm info

Pasture intake	1.61	t/ha	108	kg/animal
Supp. intake	1.51	t/ha	101	kg/animal
Cut	2.70	t/ha		

Display paddock 1

Select the paddock to display on the interface. This can also be done by clicking on the grid