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Lime, phosphorus and stocking rate of an extensively managed permanent pasture affect feed-on-offer, sheep growth rate, carrying capacity and wool production

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ABSTRACT

Context. Soil acidity constrains pasture productivity, limiting production from grazing animals. Lime application can ameliorate acidity, although the rate is increased when incorporated rather than surface applied. Soils in south-eastern Australia are generally highly erodible, containing valuable native grasses that might be lost if disturbed. Surface application is, therefore, the only option, but the extent to which lime can ameliorate acidity and increase pasture and animal production requires research. **Aim.** This 10-year experiment studied three rates of surface-applied lime, two of superphosphate (P) and two stocking rates (SR) on continuously grazed sheep on acidic soils. Two flocks were studied, one from May 1999 to December 2002, and the second from August 2005 to July 2008. We hypothesised that wool production and animal liveweight would increase as (1) lime rate increased, (2) P rate increased, and (3) peak animal productivity would occur under the combination of the highest rates of lime and P. **Key results.** The experiment coincided with the Millennium Drought reducing forage production, and slowing lime movement into the soil and consequent amelioration. During Flock 1, effective SR (dry sheep equivalents (DSE)/ha) of the low P, low SR and limed treatment became higher by 1 DSE/ha for 10 months during the final flock measurement months, as drought intensified. During Flock 2, effective SR of both high P, high SR and limed treatments were greater by 2 DSE/ha than non-limed counterpart for the first 9 months of 2006. Trends of higher animal production under lime became clearer with time, so were more apparent in Flock 2 than Flock 1, and at higher SR. High lime, high P and high SR had the greatest wool production. High P, low SR and nil lime was initially highly productive, but declined sharply when legumes disappeared, associated with soil aluminium toxicity. Lime maintained superior ground cover under drought, reducing the danger of sward death and soil erosion, demonstrating its sward preservation, sustainability and ecosystem service benefits. **Implications.** With the ever-increasing price of land, farmers must increase their land's productivity. This trial demonstrated production and environmental benefits associated with acid soil amelioration through lime application.

Keywords: acid soil amelioration, drought effects, grazing system sustainability, ground cover, subterranean clover decline, soil aluminium toxicity.

Introduction

On many fragile, non-arable soils of the high-to-medium rainfall zone of southern Australia, grazing animal production from permanent pastures is one of the few viable forms of agriculture. Legume productivity is crucial to many of these extensive grazing systems, as N fixation is the primary source of nitrogen, as well as providing high-quality forage. Adequate phosphorus (P) nutrition is critical for maintaining legume production, although the build-up of organic matter associated with these pastures can acidify soils (Williams 1980), as can the removal of alkalinity associated with agricultural production (Sumner 1995). Soil acidity constrains pasture productivity, limiting production from grazing animals. Dolling (2001) estimated that there are 50 m ha throughout Australia with a pH_{Ca} < 5.5 and associated increase in soil exchangeable aluminium (Al_{ex}). New South Wales (NSW) alone has 13.7 m ha with strongly acid soils (pH_{Ca} < 5.0; Fenton and Helyar 1993). Areas with subsurface acidity are more difficult to define, but are estimated to comprise most of the areas with surface pH values <4.5 (i.e. ~4 m ha). Many of these areas produce meat and wool, but unlike their counterparts in the UK (Holland *et al.* 2018), many Australian farmers are uncertain of the benefits of liming, causing this question to be neglected by researchers.

Research to study the effects of reducing soil acidity by liming on grazing animal productivity has not received much attention worldwide. An early study in Victoria (Hosking *et al.* 1973) was unable to show any differences in milk production in paired paddock comparisons across an entire farm, although that work only measured effects for 3 years after lime application, and arguably compared soils on which low pH was unlikely to be the major constraint. Pivotal studies occurred earlier in New Zealand than in Australia, where Bircham and Crouchley (1976) and Bircham *et al.* (1977) undertook research quite similar to that we report here insofar as they also studied the effects of superphosphate, lime and stocking rate on pasture and animal productivity. The primary difference between these two experiments was that in New Zealand, only one lime rate (6.3 t ha^{-1}) was studied, whereas this Australian, work has considered two rates that were set according to the calculated rise in soil pH (to pH_{Ca} 5.0 and 5.5) that they should achieve. Bircham *et al.* (1977) demonstrated that ewe and lamb liveweight responded positively to lime application. These researchers showed that positive liveweight responses to lime application were most pronounced and occurred more frequently at higher rather than lower stocking rates, and they also demonstrated greater wool production per unit area under the higher stocking rate, where this was associated with lime application.

In Australia, most research has concentrated on the effects of lime incorporated into the 0–10-cm soil profile, although, incorporation is only possible where land is arable and, therefore, greater emphasis has focused on the effects of liming on annual crops and pastures in phased farming systems rather than permanent pastures (Li *et al.* 2003, 2006*a*, 2006*b*, 2019). Thus, the research of Li *et al.* (2001, 2006*a*) showed that treatments that had received sufficient lime to raise soil $pHCaCl_2$ in the 0–10-cm profile to 5.5 were able to carry 29% more stock than unlimed treatments (pH_{CaCl2} 4.1) on the perennial species-based pastures, with the outcome being that the limed paddocks produced 27% more liveweight gain and 28% more greasy wool than unlimed perennial pastures. This increased sheep productivity was observed from the second year after lime application due to a combination of greater pasture production and improved pasture quality (Li *et al.* 2006*a*).

On the NSW Southern Tablelands and in north-eastern Victoria, large areas of non-arable soils are acidic to depth and are primarily permanent pastures where the only option to ameliorate acidity is to apply lime to the soil surface. In Australia, only two studies, Bromfield *et al.* (1987) and Richardson and Simpson (1988), have compared incorporation with surface application. Their finding was that the ameliorative effects of lime move into the soil from the surface at a very slow rate following surface application. The rate of lime movement and depth attained of associated acid soil amelioration was greater for coarser textured soil, and where the initial soil pH is not so low. Although limited research has been conducted, Rowe (1982) in north-western Tasmania showed that it was possible to raise soil pH_{H2O} from 5.5 to 7.0 and forage production by 11% in early spring and 16% over summer after applications of 15 t ha^{-1} of lime.

One study in south-western Victoria indicated that the primary positive effect of lime application on pasture growth was caused by the reduction in Al_{ex} rather than the increase in pH (Quigley *et al.* 2001). Conversely, another study in south-eastern Victoria showed pasture responses to be highly variable, with the authors suggesting that lime application was likely to be uneconomical (Crawford and Gourley 2001).

In a comprehensive review of the subject, Scott *et al.* (2000) concluded that it is not possible to make definitive recommendations regarding the use of surface liming technology because of the small number of surface-applied liming experiments on permanent pasture in Australia, and the quite variable results that have been observed, providing a strong case that more research is required. Therefore, an experiment was undertaken to study the effects on soil, pasture and animal production of different levels of lime, P and stocking rate over a time period long enough to ensure that the effects of lime should be acting to ameliorate the acid soil. Analysis of the soil data from this experiment showed: (1) the ability of surface applied lime to increase soil pH and decrease concentrations of Al_{ex} at depth increased with lime rate and time since application; and (2) when applied to productive, P fertilised, legume-based pasture, the ability of lime to ameliorate acidity is improved under lower stocking density, apparently due to lower rates of acidification than at a higher stocking rate (Norton *et al.* 2018). In terms of the effect on pasture production, we hypothesised that as lime application rate increased, over time this would lead to greater forage production, with the sward comprising a higher percentage of species favourable for grazing animal production and greater groundcover, and that long-term legume production would be favoured by a higher level of applied P. Indeed, analyses of the pasture botanical composition and groundcover confirmed these hypotheses, but also showed that under high P, nil lime and low stocking rate, legume content actually declined over the long term (Norton *et al.* 2020). The increase in pasture production and improvements in pasture quality associated with lime application led to three hypotheses in the animal production aspect of the experiment here described. That wool production, animal liveweight gain and stocking rate would increase as (1) lime rate increased, (2) as P rate increased, and that (3) peak animal productivity would occur under the combination of the highest rates of lime and P.

Materials and methods

Site description

The replicated experiment, which was conducted near Sutton, NSW, Australia (35.12°S, 149.27°E), commenced with lime application and pasture sowing in autumn/spring 1998, and was continuously grazed by Merino wethers between May 1999 and July 2008. The local topography comprises low rises with flat-to-gently rounded crests, short sideslopes and narrow drainage depressions, and the site was part of a relict Tertiary terrace, relatively high in the landscape. Aspect varied considerably from plot to plot. The experiment covered an area of over 20 ha. The soils are underlain by Tertiary pebble conglomerate and Silurian metasediments (Abell 1991), with depth ranging from very shallow (<20 cm) high in the landscape to deep in the low lying areas (>1.5 m). The soils, predominately chromosols (red podzolic soils) with leptic rudosols (lithosols; Stace *et al.* 1968; Isbell 1996) in higher areas, were mainly shallow and stony with texture contrast having brown loam topsoils overlying reddish to reddish brown light clays and clay loams. Prior to imposition of the treatments, the soil was strongly acidic to depth with a pH_{Ca} ranging from 4.1 at the surface to 4.7 at 55 cm. In the 0–10 and 10–20 cm profiles, Al^{3+} saturation was very high, ranging from 30 to 48% of the effective cation exchange complex (ECEC). ECEC levels were low (4.6 cmol+/kg), as were extractable P (9.7 mg/kg, Colwell), whereas total carbon was 3% (Table 1).

The secondary grassland present on the site comprised mainly the native perennial grasses *Rytidosperma* spp., *Aristida ramosa* R.Br., *Austrostipa scabra* (Lindl.), S.W.L. Jacobs and J. Everett, *Microlaena stipoides* (Labill.) R.Br., annual grasses, and native and introduced forbs, including small amounts of introduced legumes. The presence of small amounts of phalaris (*Phalaris aquatica* L.) suggests that an attempt had been made to sow a pasture in the past. However, phalaris was very sparse and restricted to the lower slopes on the western side of the site, where soils were deeper and, generally, less acid.

Pasture improvement

In autumn 1998, prior to lime application, the herbicide, Sprayseed 250® (paraquat, diquat), was applied to remove annual grasses and broadleaved weeds, while retaining as much of the established native perennial grasses as possible. Sowing occurred in May 1998 using a direct-drill seeder at a row spacing of 30 cm, so as to only minimally disturb the established native perennial grasses, while ensuring a reasonable density of introduced pasture species. The sown mix comprised *Trifolium subterraneum* L. (subterranean clover) cvv. Goulburn and Seaton Park LF, *Dactylis glomerata* L. (cocksfoot) cv. Kara, *P. aquatica* L. cvv. Australian and Holdfast, and *Lolium perenne* L. (perennial ryegrass) cv. Roper at 5.4, 2.6, 1.75, 1.75, 1.75 and 1.75 kg/ha, respectively. All subterranean clover seed was inoculated and lime pelleted, with an additional treatment of molybdenum trioxide at approximately 100 g/ha applied to the seed.

Allocation of animals to plots, stocking rates and stock management

All procedures were approved by the NSW Department of Primary Industries Animal Ethics Committee. The enterprise targeted by the project was fine wool production. Plots were continuously grazed with Merino wethers, apart from when animals were removed from plots because of drought or lack of funding. The animal measurements did not commence until 10 May 1999, when grazing treatments of the trial were imposed.

Wethers were allocated to plots using a stratified randomisation procedure on the basis of liveweight, fleece weight and fibre diameter from a larger pool of uniform animals previously selected from a flock provided by the property owner. Surplus wethers not allocated to experimental plots were grazed in a combined mob on similar

Table 1. Soil pH_{Ca}, Al as percentage of ECEC, available P, ECEC and total C at various soil depths at Sutton, NSW prior to the commencement of the experiment in 1998.

Depth (cm)	pH_{Ca}	Al (% of ECEC)	P (mg/kg Colwell)	ECEC (cmol+/kg)	Total C (%)
0–10	4.1	30.3	9.7	4.6	3.0
10–20	4.2	47.6	5.4	3.8	1.3
20–30	4.3	Not tested	Not tested	Not tested	Not tested
30–40	4.4	"	"	"	"
40–50	4.6	"	"	"	"
50–60	4.7	"	"	"	"

areas surrounding the experimental plots. The experiment was set stocked at two stocking rates, with the lower stocking rate (SR1) being 67% of the higher rate (SR2). Stocking rates in the experiment were not fixed, but were allowed to vary due to pasture availability, and animal liveweight and condition, as shown in Table 2. However, the stocking rates within each lime × P treatment always moved together and maintained their relativity to each other, as plot sizes for low and high stocking rates were 1 and 0.67 ha respectively. The aim of stocking rate changes was to maintain liveweight of wethers at similar levels across treatments, so that increases in pasture productivity could be reflected in increases in animal product per hectare. Changes in stocking rate were generally conservative, to avoid frequent changes, and aimed to eventually reach a level that could be maintained through most seasons without adjustment or hand feeding. Extra animals for stocking rate modification (or to replace animals which died or were otherwise unsuitable) were obtained from the surplus wethers referred to previously. Animals were selected for these purposes on the basis of similar liveweight to those already on the plots. Apart from the need to replace animals due to deaths and to changes in stocking rates, the same animals were retained on each plot for several years. However, because of the long duration of the trial, three different flocks were required over the period 1998 to 2008. The times between which these different flocks were present are as follows: flock 1 – May 1999 to December 2002; flock 2 – March 2003 to July 2004 (flock 2 was never shorn and results of this flock are not presented here); flock 3 – August 2005 to October 2008.

Table 2. Dates of changes in stocking rate (SR, sheep/ha) across the different phosphorus (P1, P2), lime (L0, L1, L2) and stocking rate treatments (SR1, SR2), and periods of destocking over the duration of the experiment at Sutton, NSW.

Date/SR	P1L0	P1L1	P2L0		P2L1		P2L2	
	SR1	SR1	SR1	SR2	SR1	SR2	SR1	SR2
10/5/1999	3	3	3	4.5	3	4.5	3	4.5
3/9/1999	3	3	4	6	4	6	4	6
17/5/2000	4	4	5	7.5	5	7.5	5	7.5
3/11/2000	5	5	6	9	6	9	6	9
18/3/2001	6	6	7	10.5	7	10.5	7	10.5
9/9/2002	5	6	7	10.5	7	10.5	7	10.5
9/12/2002	5	6	7	D	7	D	7	D
19/12/2002	5	6	7	D	7	D	7	D
10/1/2003	D	6	D	D	7	D	7	D
6/2/2003	D	D	D	D	D	D	D	D
18/03/2003	3	5	5	7.5	5	7.5	5	7.5
10/06/2004	5	7	7	9.5	7	9.5	7	9.5
3/09/2004	D	D	D	D	D	D	D	D
15/08/2005	6	6	7	10.5	7	10.5	7	10.5
22/03/2006	6	6	7	10.5	7	10.5	7	10.5
6/06/2006	4	4	5	7.5	5	7.5	5	7.5
6/02/2007	4	4	5	D	5	D	5	D
2/03/2007	D	D	D	D	D	D	D	D
21/05/2007	3	3	3	D	4	D	4	D
7/06/2007	3	3	4	6	4	6	4	6
6/8/2007	4	4	5	7.5	5	7.5	5	7.5
8/11/2007	3	3	4	6	4	6	4	6
15/10/2008	3	3	4	6	4	6	4	6

D, treatment de-stocked.

Normal sheep management procedures were followed during the experiment, with wethers being drenched for worms, treated for pizzle rot and so on, as required. Crutching was performed in spring to control flystrike, and individual wethers were treated as required.

Due to below average rainfall associated with the Millennium Drought, which coincided with much of the trial duration (Verdon-Kidd and Kiem 2009), supplementary feeding while keeping animals on the plots was required on a number of occasions from February 2002 onwards, as drought conditions worsened. The main periods of supplementary feeding (with animals kept on plots) were from mid-February to the end of August 2002, April to August 2006 and late December 2006 to February 2007. The amounts of supplement required by sheep were determined on a plot-by-plot basis using the program GrazFeed® (CSIRO 2007; Freer *et al.* 2010). A revised stocking rate (dry sheep equivalent (DSE)/Ha) was calculated from the number of sheep per plot and adjusted for the amount of supplementary feed provided to the sheep during these periods. To achieve this adjustment, the metabolisable energy (ME) required (maintenance plus gain) was calculated from observed mean liveweight and liveweight change per plot (CSIRO 2007). The amount of ME supplied as supplements was then subtracted from total ME required. The stocking rate was then revised from calculation of the number of sheep that could be maintained per plot with the reduced ME available while accounting for the observed mean increased liveweight.

On some occasions, all animals were removed from plots due to lack of feed, poor animal condition or lack of finance (Table 2). At these times, the animals were placed in 'sacrifice paddocks' away from the trial and given complete feeding. The main times when this occurred because of drought were over summer 2002/2003 and the summer/autumn 2006/2007 period. The period between September 2004 and August 2005 was also destocked due to a combination of drought and lack of finance.

Design and treatments

There were three treatment factors, P, stocking rate and lime with different levels, replicated twice in an unbalanced design. The treatments were combinations of two rates of P (P1, P2), two stocking rates (SR1, SR2) and three rates of lime (L0, L1, L2), as follows: P1SR1L0, P1SR1L1, P2SR1L0, P2SR1L1, P2SR1L2, P2SR2L0, P2SR2L1 and P2SR2L2. All eight treatments received superphosphate (0-9-0-11, N, P, K, S) with, P1, using typical local application rates, 125 kg ha^{-1} every 2–3 years, whereas P2 minimised the possibility of P deficiency, applying 250 kg ha^{-1} $year^{-1}$. The applied superphosphate was fortified with molybdenum (0.05% Mo) twice during the experiment, in 2002 and 2006, years when all P treatments received fertiliser. The low P treatment was only stocked at SR1, it being considered unlikely that the high stocking rate (SR2) would be used by local graziers, whereas the high P treatment was stocked at both SR1 and SR2. Furthermore, due to logistical constraints of limited land availability, it was not possible to have a 'low P, high lime treatment' (P1L2), this also being considered a treatment of lower likelihood in commercial agriculture. Moreover, shortly after commencing the trial, it became apparent that the level of P fertilisation was a key determinant of herbage production, with substantially higher herbage production under P2. As a key rationale of stocking rate determination in the trial was to ensure that a similar level of 'herbage on offer' was available to all animals in the trial, it became necessary to establish two sets of low stocking rate for the low and high levels of P fertiliser, respectively. Three rates of lime were applied at experiment commencement: nil (L0); sufficient lime to increase pH_{Ca} in the 0–10 cm profile to 5.0 (mean rate 4.36 t ha^{-1}, L1); and lime to increase pH_{Ca} in the 0–10 cm profile to 5.5 (mean rate 7.72 t ha^{-1}, L2). All lime applied was F70 superfine (70% <75 μm particle size, neutralising value 97%).

At the beginning of the experiment, soils across the site were characterised on a plot basis by analysis of pH_{Ca}, Al_{ex}, total carbon (C), ECEC and Colwell phosphorus (P) in 10-cm profile segments from the surface to 60 cm depth (Rayment and Lyons 2010). This baseline information ensured that only plots that had similar values were included in the trial, thus ensuring that any effects observed were caused by the treatments rather than initial interplot variability. Pre-experimental soil sampling determined lime rates using the 'Lime-It' model (Liu et al. 2003). To avoid the possibility of excess lime application, half of the lime required was applied in October 1998 and the remainder in early 2000, after data on initial pH changes became available.

Experiment measurements

Incident weather, soil and pastures

A weather station to measure those parameters determining pasture and animal production was established on-site. Methods and procedures for measurement of soils have been described elsewhere (Norton et al. 2018).

Pasture measurements

Cages were not used, so herbage mass measurements were of the available feed-on-offer. Feed-on-offer and botanical composition (percentage of herbage mass) were measured in each plot every 6 weeks between March 1999 and October 2008, except from January 2003 to November 2005, when measurements were more sporadic due to drought and funding constraints. BOTANAL procedures (Tothill et al. 1992) were used combining a dry-weight-rank method (Mannetje and Haydock 1963) and a comparative yield method (Haydock and Shaw 1975). In each plot, the pasture measurements were taken in 30 fixed quadrats (dimensions 0.5 m × 0.5 m) spaced at 1-m intervals along two 15-m long permanent transects, chosen to sample the environmental variation across each plot. Sheep camping sites were avoided. Herbage mass was estimated directly as kg DM ha^{-1}.

The pasture in this experiment would often contain ≥25 species. To facilitate analyses of forage production and botanical composition, the species were placed into six groups according to their value for grazing animal production. The components of these pasture species groups are presented in Table 3. The species groups were named as follows: (1) legumes, (2) productive perennial grasses, (3) annual grasses, (4) perennial grass weeds, (5) broad leaved weeds, and (6) rushes, sedges and forbs.

Sheep and wool

Liveweight of sheep was assessed on a 6-weekly time-step immediately after the BOTANAL pasture measurements of feed-on-offer and botanical composition were undertaken. Wethers were shorn once per year. This occurred in April 1999, before wethers were allocated to plots, and March 2000, April 2001, May 2002 and April 2003. The absence of funding over most of 2004 and 2005 precluded wool production being measured over that period. In 2006, shearing

Table 3. The main constituents of the six species groups used to facilitate statistical analyses in the 'surface-applied lime permanent pasture experiment' at Sutton, NSW.

Species group name	Constituent species
Legumes	Subterranean clover, *Trifolium arvense*
Productive perennial grasses	Phalaris, cocksfoot, perennial ryegrass, *Rytidosperma* spp., *Microlaena stipoides, Austrostipa* spp., *Elymus scaber, Bothriochloa macra, Cynodon dactylon, Chloris* spp., *Paspalum dilatatum*
Annual grasses	*Vulpia* spp., *Bromus* spp., *Aira* spp., *Poa annua, Digitaria* spp., *Panicum* spp., *Hordeum leporinum*
Perennial grass weeds	*Aristida ramosa, Eragrostis* spp., *Holcus lanatus, Poa bulbosa,*
Broad-leaved weeds	*Arctotheca* spp, *Erodium* spp, *Rumex acetosa.*
Rushes, sedges, forbs	*Lomandra* spp., *Juncus usitatus, J. bufonius, Cyperus* spp.

occurred in early July, whereas in 2007 and 2008, it took place in early June. At shearing, all fleeces were weighed, and a mid-side sample of wool was collected from all fleeces. Fibre diameter was measured on individual samples from each sheep. Other parameters of wool production measured included greasy fleece weight and wool production ha^{-1}.

Statistical analyses

Linear mixed models fitted using ASReml 3.0 (Gilmour *et al.* 2009) were used to model feed-on-offer for each of the botanical components, total DM and groundcover. For 1999–2002 and 2006–2008, plot data were collected on a 6-weekly basis (except for one occasion), and these data are henceforth referred to as Set 1. In the years 2003–2005, data collection was less frequent, occurring in 2003 in May, April and June in 2004, and December in 2005. These data will be referred to as Set 2. Treatments were grouped based on P rate (P1, P2), lime rate (L0, L1, L2) and stocking rate (SR1, SR2). The treatment groupings were as follows: P1 by lime $_{(L0\ or\ L1)}$ by stocking rate $_{(SR1)}$ and P2 by lime $_{(L0,\ L1\ or\ L2)}$ by stocking rate $_{(SR1,SR2)}$. Thus, only some P by L by SR interactions are able to be estimated. For Set 1, a factor *f* of two levels was established to distinguish between the years: 1999–2002 (f = 1) and 2006–2008 (f = 2). Set 1 data were modelled over months using the cubic smoothing splines methods of Verbyla *et al.* (1999), with separate splines developed for the periods f = 1 and f = 2 by use of the at(f,1) and at(f,2) commands. Set 2 data were modelled separately to Set 1, and included fixed effects for year, month within year (2004 only), and P, L and SR, and all estimable multiway interactions of these factors within each year by month combination. The full details of these analyses are described in Norton *et al.* (2020).

As two independent flocks of different animals were monitored for this study, analyses were performed separately for Flock 1 and Flock 2. The sheep of Flock 1 were continuously monitored for 1297 days over the period from May 1999 to October 2002, and those of Flock 2 for 1073 days over the period from August 2005 to July 2008, where the sheep weights were recorded on a 6-weekly basis over the years.

One of the primary aims of the study was to assess the weight changes over the time accounting for the combined effects of all treatment levels. To investigate this objective, ASReml ver. 3 (VSN International, Hemel Hempstead, UK) in the R (R 2022) statistical software was used to perform linear mixed effects models. To account for stocking rate for the different number of sheep carried across the plots, the mean weight per plot was considered as the response variable. Eight levels of treatment, days and their interactions were included as fixed effects. To represent the daily environmental changes in the model, random cubic smoothing splines of days and its interaction with plots and treatments were included. To account for the study design, the random intercepts for plots and replicates were also added and these helped to account for random variation between plots. Based on the model, predicted mean weights per plot of all treatment levels and l.s.d. at 5% significance level were computed for every 6 months, and reported in Table format.

We then evaluated the impact of lime on stocking rate, expressed as DSE ha^{-1} for a given combination of levels of superphosphate (P1 and P2) and stocking rate (SR1 and SR 2). This required three independent analyses (P1SR1, P2SR1 and P2SR2) to be performed for each flock due to allocation of treatments in the design. Again, the linear mixed effects model was used to evaluate the lime impacts on DSE, where fixed effects in the models were lime, days and their interactions, and random effects in the models were cubic smoothing splines of days and their interaction with plots plus plots and replicates. Based on the fitted models, prediction of the stocking rate and l.s.d. at given time points of Flock 1 and Flock 2 were computed and displayed in graphical formats.

The various wool production parameters from each annual shearing (greasy fleece weight, fibre diameter, wool production ha^{-1}) from each flock were analysed separately by ANOVA using the general analysis procedure within Genstat 20 (VSN International, Hemel Hempstead, UK). The three treatment – variables, lime, P and stocking rate – were combined into a single fixed factor termed 'treatment', which had eight levels. The random factor was 'replication'. In all of the above analyses, checking of residuals within the respective programs ensured assumptions regarding normality were met.

Results and discussion

The primary aim of this long-term grazing experiment was to answer the often-debated question of whether it is worthwhile for graziers to ameliorate the soil acidity of their permanent pastures by surface application of lime.

Seasonal conditions

Close to average seasonal conditions only occurred in three out of the 10 years of the experiment (Table 4). Years with particularly low rainfall included 2002, 2004, 2006 and 2008.

Consequently, pasture growth rates were low at these periods, and animals were fed supplements or plots destocked. The stocking rates varied in accordance with the level of available forage, and these together with periods of destocking are presented in Table 2.

This complicating factor must be considered when interpreting the results. This phenomenon, termed The Millenium Drought (Verdon-Kidd and Kiem 2009), coincided with much of the experiment, and when compared with average conditions, this is likely to have reduced the benefits of lime during the trial in a number of ways. First, the drought

Table 4. Long-term average annual and monthly rainfall (LTA) at a location (The Anchorage, Sutton) nearby to the experimental site in comparison with actual site annual and monthly rainfall over the experimental duration (January 1999–October 2008) near Sutton, NSW.

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1999	115	13	100	44	33	35	22	46	63	142	30	125	768
2000	26	14	65	75	69	30	35	69	70	59	96	26	634
2001	45	121	48	8	3	42	30	66	76	38	40	11	529
2002	18	189	22	11	30	37	16	27	51	5	9	28	443
2003	12	56	45	16	18	57	48	80	38	68	65	68	572
2004	46	22	8	6	4	14	18	56	38	57	69	81	420
2005	51	60	25	10	1	54	106	50	103	62	96	28	645
2006	87	17	24	20	9	98	43	22	11	3	31	11	375
2007	11	61	37	34	40	110	26	16	12	29	80	95	550
2008	83	51	42	26	15	36	51	34	28	25	–	–	391
LTA	57	54	48	42	40	47	48	52	56	57	70	57	628

would have slowed the movement of lime down the profile and, thereby, reduced the rate of acid soil amelioration (Norton *et al.* 2018). Second, the drought certainly reduced pasture production and quality (Norton *et al.* 2020), with the implication that both factors would have had flow-on, negative impacts on production, be it animal growth rate or wool production. Notwithstanding this, there were positive animal production benefits from lime application, with the benefits tending to be clearer and greater with time, and as the lime application rate increased.

Feed-on-offer

Amounts of legume, primarily subterranean clover (Fig. 1*a*, *c*, *e*) and the species group productive perennial grasses on offer (Fig. 1*b*, *d*, *f*) showed substantial variation over the experiment duration, with much of this being strongly influenced by temporal distribution of rainfall. The highest quantities of feed-on-offer of both species groups occurred in 2000/2001, when moderate levels of rainfall fell on pasture swards, which were well enough established to take full benefit of the rainfall. Thus, although 1999 was the wettest year of the trial, the pasture swards were neither fully established nor showing any ameliorative effects of lime application, and so were not able to take full production advantage of the incident rainfall (Norton *et al.* 2018, 2020).

The treatment, P2SR1L0, had the highest amount of legume-on-offer from the start of observations in 1999 until late 2002, when a major fall in production occurred, after which time, it was continually at the lower end of productivity of the eight treatments (Fig. 1*c*). Even with the near average rainfall of 2005, minimal recovery of legume content in P2SR1L0 was observed. The periods when rainfall was higher towards the end of the trial; for example, 2005 and 2007, were able to best highlight treatment effects, as otherwise drought, because of its constraining effect on plant growth, tended to mask these effects. Thus, near the end of 2005, P2SR2L1 had a high level of feed-on-offer (Fig. 1*e*), whereas in 2007, all three high stocking rate P2 treatments (P2SR2L0, P2SR2L1, P2SR2L2) had large quantities of feed, as did also the lower stocking rate, limed, P2 treatments (P2SR1L1, P2SR1L2; Fig. 1*c*). In the final year of the trial, 2008, the notable observations were the decline in legume production of the three high stocking rate P2 treatments (P2SR2L0, P2SR2L1, P2SR2L2), the relatively high production of the two limed, low stocking rate, P2 treatments (P2SR1L1, P2SR1L2), the low production in both P1 treatments (P1SR1L0, P1SR1L1) and the P2 low stocking rate treatment with no lime (P2SR1L0; Fig. 1*a*, *c*, *e*).

Whereas legume feed-on-offer tended to develop over a short time, evidenced by the sharp early production peaks (Fig. 1*a*, *c*, *e*), quantities of feed-on-offer of the productive perennial grasses group was spread over a longer period, causing the availability peaks and troughs to be smoother (Fig. 1*b*, *d*, *f*). This was primarily because the multiple species making up this group have a range of different growth rhythms, allowing them to grow over a wider range of temperatures, with their deeper root systems able to access more water than the shallow-rooted, subterranean clover, thus enabling a longer period of growth. The higher stocking rate treatments (P2SR2L0, P2SR2L1, P2SR2L2; Fig. 1*f*), with the exception of 2005, generally had lower levels of feed-on-offer than the lower stocking rates. Moreover, grass availability in the low P treatments (P1SR1L0, P1SR1L1; Fig. 1*b*) was not constrained as much as was legume availability. In the early years of the trial, the presence of lime seemed to assist production, so that in 2001, both P1SR1L1 and P2SR1L1 (Fig. 1*b*, *d*) had large quantities of grass biomass. However, towards the end of the trial in 2007 and 2008, the low stocking rate treatments without lime (P1SR1L0, P2SR1L0) had higher perennial grass biomass than other treatments, even though the overall level was

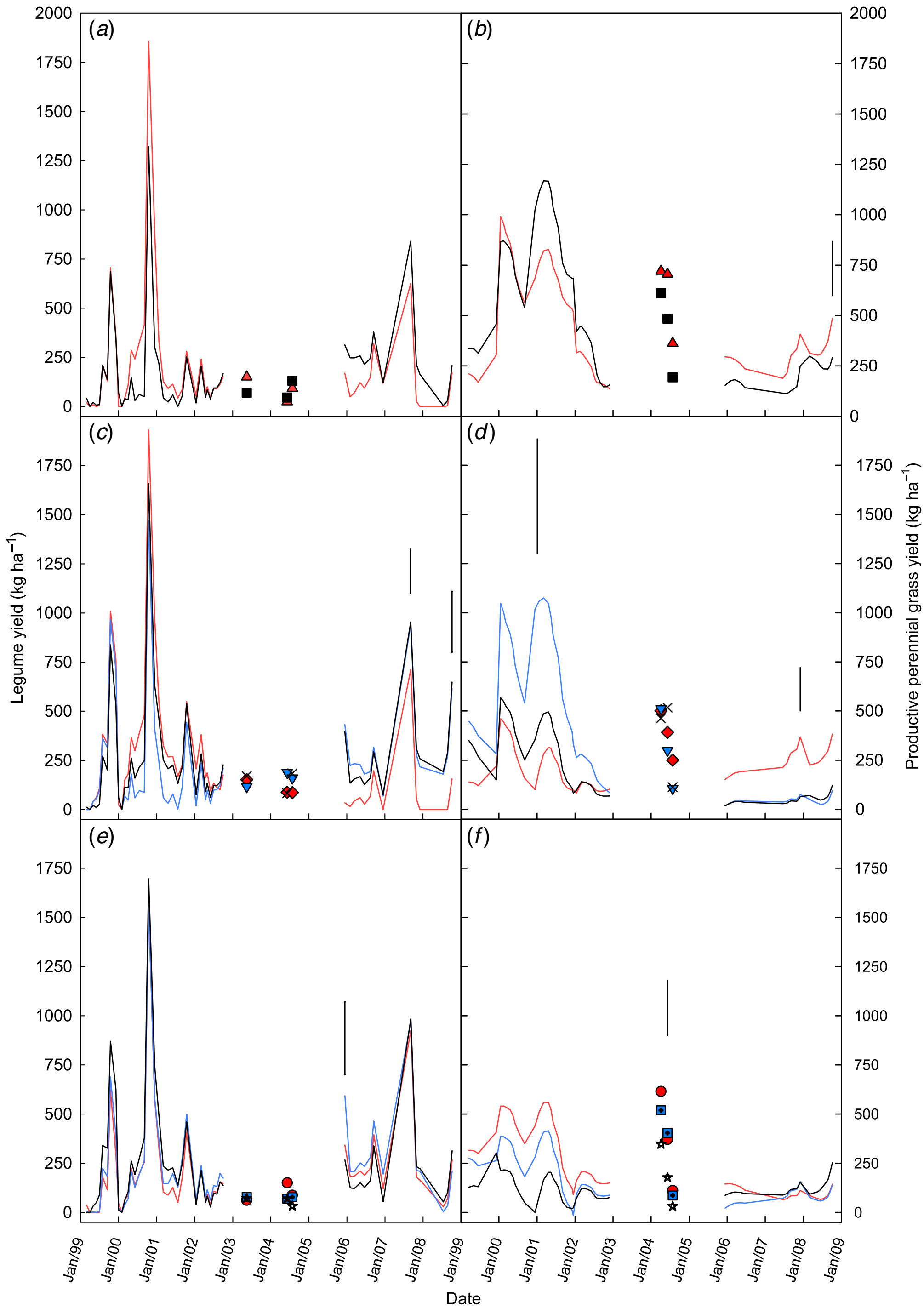

Fig. 1. The time course between 1999 and 2008 of legume DM feed-on-offer (kg ha^{-1}, *a*, *c*, *e*) and productive perennial grass feed-on-offer (kg ha^{-1}, *b*, *d*, *f*), as affected by differing levels of surface applied lime (L0, L1, L2), superphosphate (P1, P2) and two stocking rates (SR1, SR2), in the treatments P1SR1L0 (red line, Δ), P1SR1L1 (black line, ■) (*a*, *b*), P2SR1L0 (red line, ◊), P2SR1L1 (blue line, ∇), P2SR1L2 (black line, ■) (*c*, *d*), P2SR2L0 (red line, ○), P2SR2L1 (blue line, ⊡) and P2SR2L2 (black line, ★) (*e*, *f*) at Sutton, NSW, Australia. Lines cover trial periods of frequent measurement when spline analyses were used, which straddled a period of less frequent measurement signified by point-in-time observations. Vertical bars represent least significant differences (P < 5%) between all the eight treatments at specific measurement times. Bars are positioned in the frame/s of the significantly different treatment comparison, but apply equally to the other related graphs.

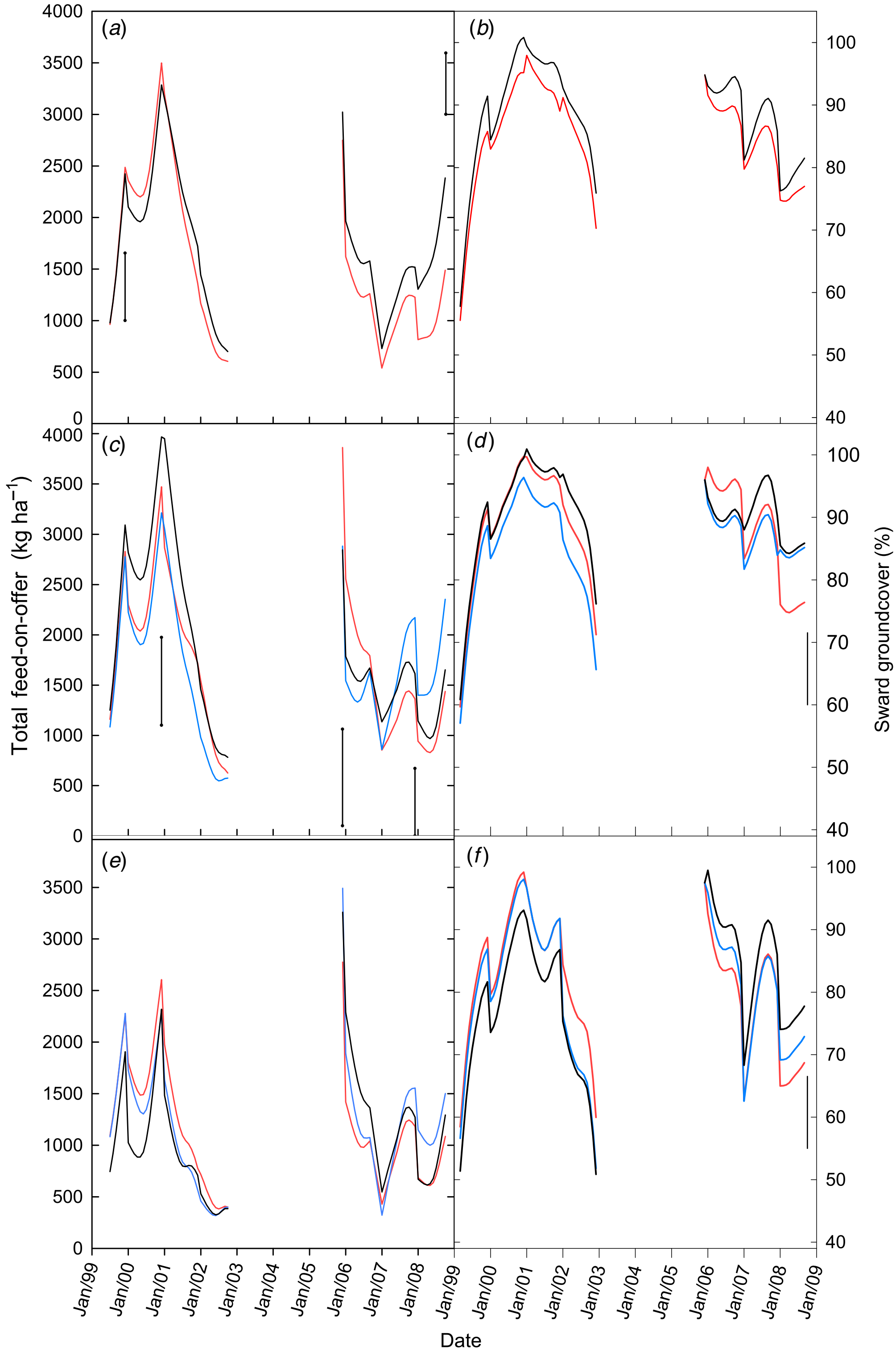

Fig. 2. The time course between 1999 and 2008 of total sward feed-on-offer (*a*, *c*, *e*) and groundcover (*b*, *d*, *f*), as affected by differing levels of surface applied lime (L0, L1, L2), superphosphate (P1, P2) and two stocking rates (SR1, SR2), in the treatments P1SR1L0 (red line), P1SR1L1 (black line) (*a*, *b*), P2SR1L0 (red line), P2SR1L1 (blue line), P2SR1L2 (black line) (*c*, *d*), P2SR2L0 (red line), P2SR2L1 (blue line) and P2SR2L2 (black line) (*e*, *f*) at Sutton, NSW, Australia. Lines cover trial periods of frequent measurement. Vertical bars represent least significant differences ($P < 5\%$) between all the eight treatments at specific measurement times. Bars are positioned in the frame/s of the significantly different treatment comparison, but apply equally to the other related graphs.

quite low (Fig. 1*b*, *d*). However, these observations may also be associated with the very low level of legume production in those treatments, because their competition may have been detrimental to the legume (Dear *et al.* 1998).

When considering total sward feed-on-offer, the higher stocking rate treatments (SR2) generally had lower quantities present than the lower stocking rates (Fig. 2*a*, *c*, *e*), with the exception of the single one-off measurement in December 2005. Although all SR2 treatments received high levels of P (P2), the high stocking rates presumably caused there to be less standing forage on the pasture most of the time. The addition of lime, particularly where associated with a lower stocking rate, seemed to be associated with high levels of total feed-on-offer, as at the end of 1999 and 2000 in P2SR1L2, and at the end of 2007 in P2SR1L1 (Fig. 2*c*). Similarly, at the end of the trial in October 2008, those treatments that received lime at a low stocking rate (P1SR1L1, P2SR1L1) were the treatments most positively responding to growing conditions with higher levels of total feed-on-offer (Fig. 2*a*, *c*).

Ground cover

At the high P level (P2), ground cover was influenced by treatment, with the frequency of significant differences due to treatment effects generally increasing with time. In P2 treatments across the experiment duration, ground cover was lower for the higher stocking rates (Fig. 2*f*; SR2) compared with lower stocking rates (Fig. 2*d*; SR1). Thus, in 2002, the first year of the trial affected by severe drought, in both P2L1 and P2L2 treatments, ground cover was lower for almost all of the year for the higher stocking rates (Fig. 2*f*) compared with the low stocking rate (Fig. 2*d*). This lower ground cover was especially apparent in December 2002, when it had fallen to 52% in the P2SR2L1 and P2SR2L2 treatment groups, whereas ground cover was maintained at 66 and 76% in the P2SR1L1 and P2SR1L2 treatments, respectively. At nil lime (L0) and high P (P2L0), any detrimental effect of the higher stocking rate (P2SR2L0) on ground cover (59%) at the end of 2002 in comparison with P2SR1L0 (71%) just failed to be statistically significant at $P = 0.05$. For much of the rest of the experiment, through to October 2008, the higher stocking rates allowed less ground cover than the lower stocking rates (Fig. 2*b*, *d*, *f*). Moreover, every treatment without lime, P1SR1L0, P2SR1L0 and P2SR2L0 ended the trial in October 2008 with lower ground cover than the limed treatments with which they were compared (Fig. 2*b*, *d*, *f*).

Sheep weights Flock 1: 1999–2002

Sheep weights were monitored during the period from May 1999 to November 2002. Average weights per paddock were recorded on a 6-weekly timestep, except in March, when they were weighed twice, prior to and after shearing. Weighing also occurred on a small number of other occasions to assist management when drought conditions were intense.

Sheep weight changed over the course of the experiment, and the interaction between treatment and time (days) was significant ($P < 0.1\%$). Overall, sheep weights tended to increase over the first 18 months of the experiment, whereas thereafter, the weights declined across all treatments, as the effect of declining feed availability caused by intensifying drought conditions prevailed (Table 5).

At the start of the experiment, individual animal weights of Flock 1 were very similar across all treatments. As the experiment progressed over time, the highest individual weights were consistently achieved under treatment combinations comprising P2SR1L2, followed by treatments comprising P2SR1L1. Conversely, the lowest individual weights were observed under treatment combinations comprising P2SR2 L1 across all observations, except at 6 months and 42 months after trial commencement, when treatment P1SR1L0 had the lowest individual weights (Table 5).

There were no significant differences in mean sheep weights across the treatments from the beginning of the trial (Day 1) until 24 months, with weights over this period increasing with time and ranging from 49.1 to 71.0 kg per animal per treatment. However, at 30 months from

Table 5. Predicted mean sheep weight (kg) of Flock 1, as affected by different levels of P, lime and stocking rate at 6-monthly observation intervals over the period from May 1999 to November 2002 at Sutton, NSW.

	P1-SR1-L0	P1-SR1-L1	P2-SR1-L0	P2-SR1-L1	P2-SR1-L2	P2-SR2-L0	P2-SR2-L1	P2-SR2-L2	l.s.d.
Day 1	48.57	49.15	49.23	50.00	50.89	49.54	49.79	50.65	5.68
6 months	58.81	59.93	60.72	61.21	61.49	59.24	59.56	61.22	4.68
12 months	55.22	56.66	58.11	58.04	58.01	54.99	55.27	57.32	4.61
18 months	67.43	68.74	71.02	70.16	70.4	66.74	66.62	68.70	4.8
24 months	63.52	64.95	68.43	66.93	67.78	63.20	62.51	64.60	4.84
30 months	60.92	63.16	67.53	65.96	67.56	61.52	60.15	62.66	4.67
36 months	59.91	63.76	66.95	67.00	68.72	61.78	59.63	62.40	4.5
42 months	58.32	64.07	64.66	67.57	68.87	61.48	58.66	61.45	4.98

l.s.d. at $P < 5\%$.

trial commencement, sheep weights were significantly greater within low stocking rate treatments (SR1) compared with the higher stocking rate (SR2) for a given combination of P2, irrespective of the lime treatment. Similarly, in the treatment combinations of low stocking rate with no lime (SR1 L0), the sheep weight was significantly higher in P2 treatments (P2SR1L0) compared with the P1 treatments (P1SR1L0). Within the P2 treatments, the mean weight was significantly greater under low stocking rates with no lime compared with high stocking rates with L1 and L2 treatments; and these same results were repeated at 36 and 42 months. In addition, at 42 months under the low stocking rate of P1, sheep weight was higher where lime (L1) was added compared with no lime application (Table 5).

Sheep weights Flock 2: 2005–2008

The second flock of sheep was studied during the period from August 2005 to July 2008. This flock started with smaller animals (22.4–23.4 kg) compared with the first flock (48.7–50.9 kg). Weights per animal were again recorded on a 6-weekly timestep, except during March of each year, when they were measured twice (pre- and post-shearing), and some other months when weighing was necessary to assist management when fodder became limited due to drought conditions. The weights tended to increase over most of the period in all treatments, except during the last 6 months in 2008, when weights declined due to drought (Tables 4 and 6). There was a significant interaction effect between treatments and time (days; $P < 0.1\%$) on the weights.

The predicted mean sheep weights of Flock 2 at 6-monthly intervals are given in Table 6. There was no significant difference between initial weights at the beginning of measurements of Flock 2 across all treatments. Similar to Flock 1 results, the highest weights were consistently observed in treatments P2SR1L2, P2SR1L1 and P1SR1L0. The lowest weights were observed in treatment P2SR2L0 across all observations. After 12 months and until the end of the experiment at 36 months, weights of P2SR2L0 tended to be the lowest of all treatments and were significantly lower than those of the lower stocking rate (SR1) treatments.

Predicted stocking rate (DSE)

Although stocking rate is a contributing factor in the trial analysis (Table 2), the fact that lime caused different sheep weights meant that the DSE carried by the treatments could differ, even if the number of sheep on two different treatments was the same (Fig. 3).

Flock 1

Across all Flock 1 treatments, stocking rates when animals entered the trial in May 1999 were at a low level (approximately 2 and 4 DSE/ha for low and high stocking rates, respectively), but were able to rise almost continually until December 2000 to approximately 8, 10 and 12 DSE/ha for P1SR1, P2SR1 and P2SR2 respectively, except for a temporary check in autumn 2000 (Fig. 3*a*, *c*, *e*). The biggest effects due to lime application in Flock 1 occurred between the low P, low stocking rate treatments, P1SR1L0 and P1SR1L1 (Fig. 3*a*) from March to December 2002, which coincided with the first extended period of severe drought conditions and the final 10 months of Flock 1 measurements. Differences in predicted stocking rate between these treatments were in excess of 1 DSE/ha for the spring and early summer of 2002 (August to December). The sheep in neither treatment received any supplementary, on-plot feeding, so the greater carrying capacity of P1SR1L1 was due to greater available fodder resulting from the lime application.

Just as with P1SR1 treatments, February to December 2002, the period of greatest drought intensity experienced by Flock 1, was the time when significant differences in carrying capacity became apparent in the P2SR1 treatments, with P2SR1L2 having significantly greater carrying capacity than P2SR1L0 (Fig. 3*c*). However, in this case, the differences due to lime application were not as great as they were in the P1SR1 treatments, not exceeding 0.5 DSE/ha. A point to remember, though, in considering these results is that

Table 6. Predicted mean sheep weights (kg) of Flock 2, as affected by different levels of P, stocking rate and lime at 6-monthly observation intervals over the period from August 2005 to August 2008 at Sutton, NSW.

	P1-SR1-L0	P1-SR1-L1	P2-SR1-L0	P2-SR1-L1	P2-SR1-L2	P2-SR2-L0	P2-SR2-L1	P2-SR2-L2	l.s.d.
Day 1	22.59	23.41	22.36	23.09	22.92	22.86	23.16	22.72	4.96
6 months	35.52	35.97	34.82	36.15	36.06	33.52	34.37	34.14	4.13
12 months	42.50	42.03	40.91	42.82	42.48	38.34	39.43	39.40	4.12
18 months	56.24	54.32	53.40	55.41	54.86	50.78	51.77	51.57	4.24
24 months	61.11	58.06	58.19	58.69	59.19	55.46	56.02	55.96	4.19
30 months	75.53	72.53	74.25	72.00	74.40	69.95	70.69	70.59	4.13
36 months	67.37	65.50	68.74	63.77	67.32	61.54	63.65	62.712	4.80

l.s.d. at $P < 5\%$.

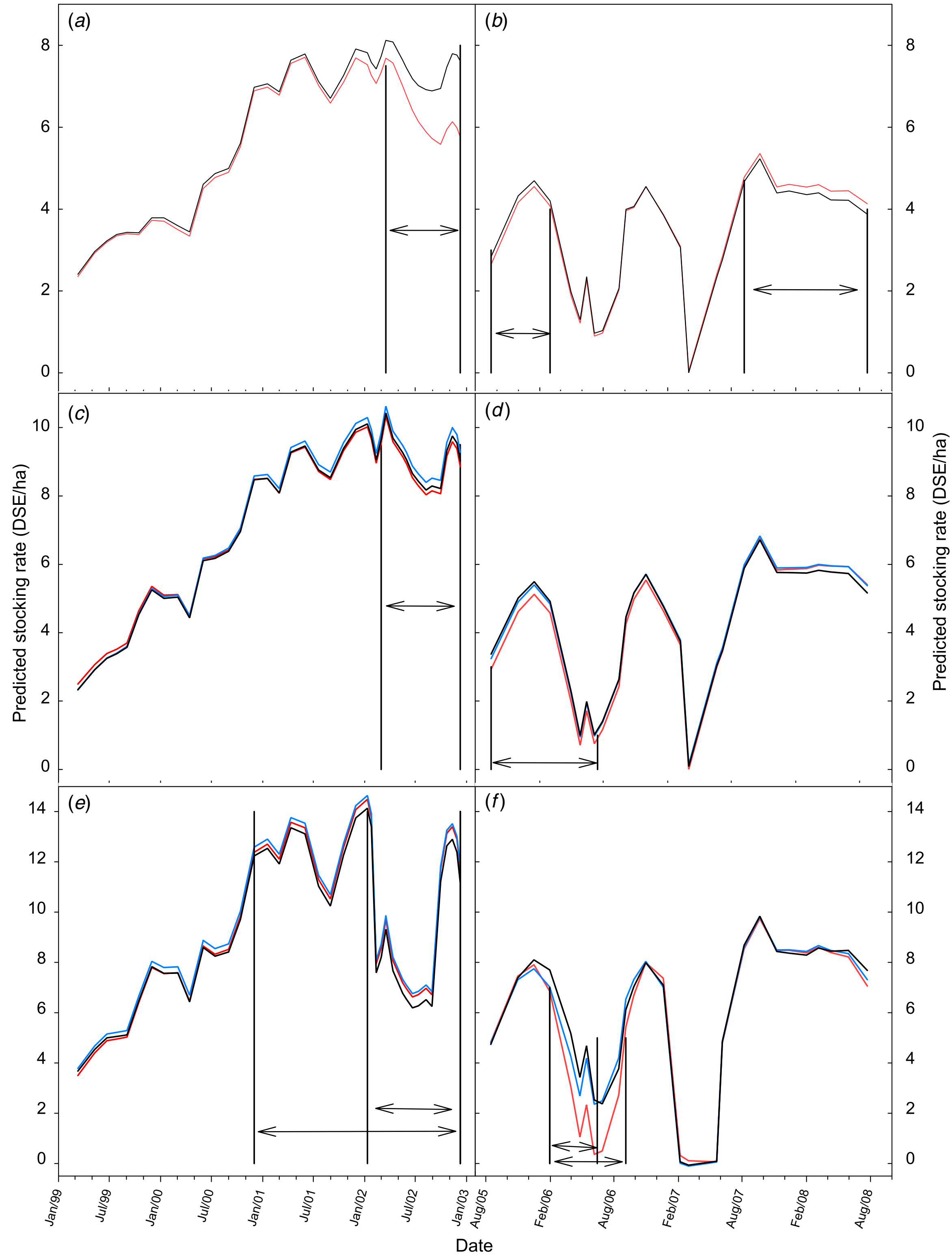

Fig. 3. Predicted stocking rates (mean number of dry sheep equivalents (DSE)/ha) of Flock 1 (*a*, *c*, *e*), over the period from May 1999 to November 2002 and Flock 2 (*b*, *d*, *f*) over the period from August 2005 to July 2008 of low P, low stocking rate treatments (*a*, *b*), P1SR1L0 (red line) and P1SR1L1 (black line); high P, low stocking rate treatments (*c*, *d*), P2SR1L0 (red line), P2SR1L1 (black line), P2SR1L2 (blue line), high P, high stocking rate treatments (*e*, *f*), P2SR2L0 (red line), P2SR2L1 (black line) and P2SR2L2 (blue line), as affected by different levels of lime at Sutton, NSW. Horizontal arrows indicate the time periods during which least significant differences ($P < 5\%$) in stocking rate occurred between treatments.

the P2SR1 stocking rates from very early in the trial were higher than those of P1SR1 (Table 2), as the higher P fertilisation of P2 produced much more forage than the P1 treatments where P deficiency limited pasture production.

In the high stocking rate treatments, significant differences due to lime between P2SR2L2 and P2SR2L0 occurred for a longer period, two complete years (December 2000–2002), than in either the P1SR1 or P2SR1 treatments (Fig. 3e). During the period from January to December 2002, P2SR2L0 also had a significantly higher stocking rate than P2SR2L1, although as with the differences between P2SR2L0 and P2SR2L2, the magnitude of difference was small, being rarely >0.5 DSE/ha.

Flock 2

Difficulties in procurement of sheep of similar weight at the beginning of Flock 2 in August 2005 were the cause of the minor differences in stocking rate over the first few months of this flock, which were present in P1SR1 (Fig. 3b) and P2SR1 (Fig. 3d) treatments. However, these differences disappeared quite rapidly. All treatments followed broadly similar trends in stocking rate, with an initial early rise from August to December 2005, followed then by steep falls through April and June 2006 due to the onset of another period of drought. During this 2006 drought period, the largest differences in stocking rate present during Flock 2 occurred in the P2SR2 treatments with both limed treatments, P2SR2L1 and P2SR2L2, carrying up to 2 DSE/ha more than the unlimed P2SR2L0 from January through to September 2006 (Fig. 3f).

Across the whole experiment, stocking rates rose throughout spring of 2006, peaking in October, after which steep declines occurred to very low levels from February to June 2007, accompanied by either supplementary feeding or destocking. P1SR1L0 subsequently had slightly higher stocking than P1SR1L1 over the last year (August 2007 to July 2008), although these differences were generally only of the order of ≤0.25 DSE/ha.

Wool production of Flock 1: experiment Years 2, 3, 4 and 5 (2000–2003) after lime application

Greasy fleece weight (kg hd^{-1}) was not significantly different between any of the eight treatment groups during Flock 1, with weights ranging from 8.1 to 6.7 kg in 2000, 7.8 to 6.1 kg in 2001, 6.55 to 4.95 kg in 2002 and 4.85 to 4.25 kg in 2003.

Fibre diameter was also not significantly affected by treatment, with diameter (μm) ranging from 23.4 to 21.5 in 2000, 22.9 to 21.2 in 2001, 22.1 to 19.7 in 2002 and 21.1 to 19.6 in 2003.

Over the first three shearings, wool production ha^{-1} generally increased with time; however, it decreased by approximately 35% in Year 5 (shearing of 2003) across all treatments (Table 7), presumably because of the decline in the feedbase caused by the drought conditions experienced in the previous year. Although greasy fleece weight and fibre diameter were not affected by treatment, wool production per hectare ($kg.ha^{-1}$) was affected ($P < 5\%$) during Flock 1 (Table 7). Across all four shearings, wool production ($kg.ha^{-1}$) was higher under the three highest stocking rate treatments (P2SR2L0, P2SR2L1, P2SR2L2) compared with the lower stocking rates (P1SR1L0, P1SR1L1, P2SR1L0, P2SR1L1, P2SR1L2). However, wool production was not significantly different between the three high stocking rate treatments, except for 2000, a year of near average rainfall, when the high lime treatment, P2SR2L2, had significantly greater wool production than its nil lime counterpart, P2SR2L0.

Wool production of Flock 2: experiment Years 8, 9 and 10 (2006–2008) after lime application

There were differences ($P < 5\%$) due to treatment in greasy fleece weight/sheep (Table 8) in trial Years 8 (2006) and 9 (2007). Greasy fleece weight in 2006 was greatest in those treatments with the highest lime rate (P2SR1L2, P2SR2L2) or where lime was applied, but at a lower stocking rate (P1SR1L1, P2SR1L1). In 2007, it was generally the highest stocking rate treatments (SR2) that had the lowest fleece weights, although it is noteworthy that this did not occur

Table 7. Wool production (kg ha^{-1}) of Flock 1, 2, 3, 4 and 5 years after lime application (2000, 2001, 2002 and 2003) from eight treatments with differing P, lime and stocking rates at Sutton, NSW. Values with different subscripts are significantly different ($P < 5\%$).

Treatment	2000-Year 2	2001-Year 3	2002-Year 4	2003-Year 5
P1 SR1 L0	23.7a	35.1a	33.9a	22.33a
P1 SR1 L1	22.8a	32.2a	33.6a	24.48a
P2 SR1 L0	28.78a	41.5ab	45.8bcd	22.84a
P2 SR1 L1	25.85a	36.6a	40.2ab	27.59ab
P2 SR1 L2	25.85a	38.8a	43.4abc	31.12bc
P2 SR2 L0	36.85b	50.3bc	52.0cde	33.47cd
P2 SR2 L1	40.7bc	55.7c	55.6de	35.44cd
P2 SR2 L2	44.27c	59.8c	60.9e	37.01d
l.s.d. $P < 5\%$	6.916	10.77	11.44	5.77

Table 8. Greasy fleece weight/sheep (GFW, $kg.hd^{-1}$) and wool production ($kg\ ha^{-1}$) of Flock 2 over Years 8, 9 and 10 after lime application (2006, 2007, 2008) from eight treatments with differing P, lime and stocking rates at Sutton, NSW. Values with different subscripts are significantly different ($P < 5\%$).

Treatment	2006-Year 8		2007-Year 9		2008-Year 10
	GFW wt	$kg\ ha^{-1}$	GFW wt	$kg\ ha^{-1}$	$kg\ ha^{-1}$
P1 SR1 L0	2.58abc	15.45e	4.35ab	17.4e	17.63d
P1 SR1 L1	2.78a	16.65e	4.4ab	17.6e	19.38d
P2 SR1 L0	2.48bcd	17.36de	4.01bcd	20.05d	24.85c
P2 SR1 L1	2.71ab	18.97cd	4.44a	22.2c	24.75c
P2 SR1 L2	2.84a	19.88c	4.24ab	21.2cd	25.27c
P2 SR2 L0	2.28d	23.94b	3.68d	27.6b	32.89b
P2 SR2 L1	2.32cd	24.36b	3.8cd	28.5b	35.16ab
P2 SR2 L2	2.74ab	28.77a	4.19abc	31.43a	37.28a
l.s.d. $P < 5\%$	0.289	2.24	0.429	2.10	3.00

under high lime P2SR2L2 application. In trial Year 10 (2008), there were no significant treatment differences with fleece weights/sheep ranging from 5.25 to 6.1 kg. By contrast, fibre diameter was not significantly different between any of the treatments across the three shearings that occurred in Years 8, 9 and 10 of the trial, with diameter (μm) ranging from 16.35 to 17.95 in 2006, 18.4 to 19.4 in 2007 and 19.5 to 20.95 in 2008.

For 'wool production per ha', differences due to treatment occurred at each of the experiment's three annual shearings (Table 8). Just as in Flock 1, the three higher stocking rate treatments (SR2) produced the most wool per unit area, although it is important to note that the treatment with the highest lime rate (P2SR2L2) always had significantly greater wool production ($P < 5\%$) than its counterpart with the high stocking rate and no lime (P2SR2L0).

Treatment effects on sheep weights

In Flock 1, the treatments with the highest individual sheep weights were those with a high level of P application (P2) and low stocking rate (SR1), because the higher soil fertility generally led to greater herbage production with a higher proportion of legume (Norton *et al.* 2020), whereas the lower stocking rate allowed a higher level of available feed to be on offer to each animal. In Flock 2, individual animal weight results were broadly similar to those observed in Flock 1, where the treatments with the highest weights were those with a high level of P fertility (P2) and low stocking rates (SR1). In both flocks, treatments with the lowest individual weights were those with the highest stocking rate (SR2).

Treatment effects on predicted stocking rate

Perhaps more important in the context of animal production than individual animal weight is stocking rate, as this is the variable that determines animal production per unit area, with higher stocking rates generally producing greater animal production per unit area. Nevertheless, the setting of stocking rate should be a compromise that ensures that animals are able to grow satisfactorily while being maintained in good health and condition. Similarly, it is essential that pastures are not over-grazed, with maintenance of a safe level of ground cover, all ensuring that animal production from the pasture is sustainable.

Given the early stage of the experiment and the known slow rate at which lime is known to move into the soil, any effects on stocking rate due to lime application during Flock 1 were, as expected, rare. However, it is noteworthy that the largest effects due to lime during Flock 1 occurred between the low P, low stocking rate treatments, P1SR1L0 and P1SR1L1. P1SR1L1 maintained a stocking rate >1 DSE/ha greater than P1SR1L0 for the period between March and December 2002. This coincided with the first extended period of severe drought conditions in the trial, and was the final 10 months of Flock 1 measurement. However, above average rainfall (189 mm; Table 2) fell in February 2002, immediately before the onset of drought. This rain is likely to have replenished subsoil moisture, making it possible for plants whose root growth was not constrained by high levels of Al_{ex} to access this moisture and produce greater amounts of forage. Lime had been applied to the plots in 1998, so this period of measurement was the longest time since treatment establishment, thus giving the lime the greatest possibility for soil amelioration and reduction of levels of Al_{ex} deeper in the profile. Indeed, soil analyses showed that the level of Al_{ex} in the soil profile <10 cm was reduced in limed plots, whereas such reductions did not occur in unlimed treatments (Norton *et al.* 2018). This is an important positive result for lime application, and one could reasonably hypothesise that the applied lime of P1SR1L1 allowed greater root exploration, giving the pasture plants the ability to extract more soil water during the drought. In turn, this would have allowed the greater production of perennial grasses (Fig. 1*b*) and total feed-on-offer (Fig. 2*a*), enabling the higher carrying capacity observed in this treatment. It is equally important to note that although P1SR1L1 carried a greater number of animals during this time, it was still able to maintain a superior groundcover than its non-limed counterpart, P1SR1L0 (Fig. 2*b*). This means that the lime conferred both greater productivity and superior sustainability to the pasture.

The greatest treatment differences in Flock 2 stocking rates occurred under the high stocking rate treatments (SR2, Fig. 3*f*), with both P2SR2L1 and P2SR2L2 carrying up to 2 DSE/ha more than the unlimed P2SR2L0 from January through to September 2006. It was noteworthy that 2006 was another year of quite intense drought during the experiment, although it is important to note that above average rainfall fell in 2005 and over the summer of 2005/2006, so it is likely that subsoil moisture reserves were replenished during that time. It is again (as with the greater carrying capacity of P1SR1L1 seen in March to December 2002) reasonable to hypothesise that the applied lime, by reducing Al_{ex}, facilitated root exploration deeper into the profile, allowing plants to access more water and produce more forage (Hayes *et al*. 2016). Conversely the decline of legume content in P2SR1L0 and the fact that this treatment had the highest levels of Al_{ex} in the 10–20 cm profile (Norton *et al*. 2018) would be likely to have constrained root development and water uptake, and threatened plant survival in drought. This provides evidence of the detrimental effects that the non-ameliorated soil condition had on legume content, a component crucial to maintenance of stocking rate. For the high stocking rate limed plots to be able to carry an extra 2 DSE/ha than the unlimed treatment for the 9 months of 2006 indicates again the advantages that lime application can confer to pasture production during both a time when water would have been non-limiting (autumn 2006) and when moving into a period of increasing water limitation when good root exploration would have been essential for ongoing forage production. Another period of treatment differences in carrying capacity deserving comment are the differences between P1SR1L0 and P1SR1L1 occurring between September 2007 and July 2008. During this period, the stocking rate was 0.25 DSE/ha higher for P1SR1L0 compared with the P1SR1L1 treatment. These results are the opposite to those observed in 2002 between these two treatments when P1SR1L1 carried >1 DSE/ha greater than P1SR1L0. The reason for this latter difference is not clear, particularly because P1SR1L1 had a greater amount of feed-on-offer than P1SR1L0 through the final months of the trial coinciding with this period (Fig. 2*a*). The stocking rate difference may have been associated with a lower palatability of the P1SR1L1 forage compared with that on the P1SR1L0 plots, because the forage on those latter plots would have been grazed to a lower height (Fig. 2*b*). However, it should be noted that 0.25 DSE/ha is a very small difference and would likely have minimal commercial impact.

A final point regarding treatment effects on stocking rate relates to sward groundcover (Fig. 2*b, d, f*). The higher stocking rates (SR2) generally led to lower levels of groundcover, which fell at rapid rates to <70%, the minimum level considered necessary for pasture system sustainability (Murphy and Lodge 2002), particularly during times of drought, as in the latter half of 2002. During these times, which occurred towards the end of both flocks, all the treatments with added lime maintained greater groundcover than unlimed treatments. This is an important positive result for the benefits of lime application with the positive financial effect of a requirement for less frequent pasture resowing coupled with a lower likelihood of soil erosion.

Treatment effects on wool production

Wool production/ha increased in both flocks as the stocking rate increased. This effect was present even when entering into periods of intense drought, such as 2001–2002. In this situation, however, the higher stocking rate treatments (SR2) had adverse effects on the pastures both in terms of botanical composition (decline in percentage of favourable species), feed-on-offer and ground cover (Norton *et al*. 2020). In both flocks across all treatments, there was a steady increase in greasy fleece weight and, therefore, wool production/ha with time as the sheep grew. However, in Flock 1, the intense drought conditions of 2002/2003 caused the increases that had occurred in the 3 years up to 2002 to be sharply reversed, such that in 2003, an average decline of 35% in wool production across all treatments occurred relative to that produced in 2002 (Table 7). This decline was in parallel with the drought-induced decline in sheep growth rate (and in some treatments, individual weight decline) that occurred in the period.

In Flock 2, the good performance of P2SR2L2, particularly when compared with P2SR2L0, is noteworthy, because in each of the three shearings (2006, 2007, 2008), this treatment had significantly greater wool production (Table 8). It is also noteworthy that P2SR2L2 maintained significantly higher groundcover than P2SR2L0, particularly as the trial was entering into periods of intensifying drought, as in 2002, 2006 and 2008 (Norton *et al*. 2020). Given the degradation and associated erosion that is common in permanent pastures of south-eastern Australia, the importance of this benefit in terms of maintaining farm profitability and pasture ecosystem services, and reducing the frequency of resowing should not be underestimated.

Differences in wool production between the high P, low stocking rate treatments (P2SR1L0, P2SR1L1, P2SR1L2) did not often reach significance throughout the trial (Table 8). P2SR1L2 had greater wool production than P2SR1L0 only in trial Year 8 (2006), although in all other years of Flock 2, the trend, albeit non-significant, was for greater production.

In Flock 1 (1999–2002), the early high production of P2SR1L0 was marked, although the sharp productivity decline that this treatment suffered in 2003, when its wool yield fell by 50% in comparison with 2002, was particularly noteworthy. Although the intensifying drought over this period was a factor in this decline, the loss of subterranean clover out of the P2SR1L0 sward that occurred over this same time was probably also key in the observed effects on the sheep. By contrast, over the same time, the wool yields of P2SR1L2 and P2SR1L1 fell by only 28% and 31%, respectively (Table 7), and the fact that both treatments were able to maintain significantly higher sward legume contents during this period possibly played a role in their better sheep performance (Norton *et al.* 2020).

In a similar way, significant differences in wool production between the P1SR1L0 and P1SR1L1 were not present over the course of the trial, although in the last 3 years, a trend suggested greater production in P1SR1L1 might have been beginning to develop, as in each of these 3 years, P1SR1L1 had greater production. Indeed, although some of these differences were not statistically significant in the current study, a longer period of measurement and especially measurement during more years where water was not limiting may have provided a clearer indication of potential beneficial effects of lime.

Conclusion

This trial has demonstrated that in the presence of non-limiting P, lime application can lead to increases in feed-on-offer and, as a consequence, stocking rate and wool production. This result, therefore, supported the central hypothesis of the experiment that peak animal productivity would occur under a combination of the highest rates of lime and P. In addition, the results generally supported the other hypotheses that wool production and animal growth would increase as lime and P rates increased. These effects were clearest when low soil water availability did not severely limit pasture production. The benefits of acid soil amelioration brought about by lime were also demonstrated by the preservation of groundcover, which maintains pasture system sustainability and ecosystem services. Notwithstanding, results coming out of the trial may well have been more convincing had the research taken place during a period of nearer average rainfall rather than over several years of severe drought, which quite possibly acted to reduce treatment effects.

The price of land in the medium-to-high rainfall acid soil zone of southern Australia is increasingly expensive, so that many producers are no longer able to increase production by simply purchasing more land. Farmers must, therefore, aim to increase the productivity of their land, and this trial has demonstrated production and environmental advantages associated with lime application. Thus, this research contributes to charting a path forward to improve the economic and environmental sustainability of grazing animal production on permanent pastures of the medium-to-high rainfall acid soil zone.

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