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The long-term influence of superphosphate and stocking rate on the production of spring-lambing Merino sheep in the high rainfall zone of southern Australia

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Abstract. The productivity of spring-lambing fine wool Merino sheep grazing pastures sown in 1977 to perennial ryegrass and subterranean clover was assessed from 1989 to 1998. The pastures were fertilised each autumn with single superphosphate at 6 levels, and were stocked at a low, medium, or high stocking rate (SR) at each level of fertiliser. The average phosphorus (P) applied annually since sowing ($\overline{P}$) ranged from 1.6 to 32.9 kg/ha. The SRs used varied with fertiliser level in that they were higher where more fertiliser had been applied, so that the highest SR at each level of fertiliser ensured that the pastures were well utilised. Each ewe raised 1 lamb, which was removed at weaning. The influence of fertiliser on the productivity of the sheep at 4 classes (1–4) of SR (mean SR = 7.1, 10.1, 12.6, and 18.2 ewes/ha for classes 1–4, respectively) was described by: $y = A - BC^{\overline{P}}$, where y represents production per sheep (kg), and A, B, and C are constants. For greasy fleece weight, estimates of B and C were 1.59 and 0.84; and for SR classes 1–4, the estimates of A were 5.06, 4.89, 4.78, and 4.46, respectively. For weaning weight of lambs, estimates of B and C were 8.4 and 0.82, and estimates of A were 23.5, 22.7, 21.5, and 20.9 for SR classes 1–4. The mean fibre diameter (µm) of the wool was described by: $\overline{D} = 14.18 + 1.48\,\overline{GW}$, where $\overline{GW}$ is the mean greasy wool produced annually per sheep (kg) averaged over all sheep and years for each of the 18 treatments. The price (cents/kg) of wool with a fibre diameter D (P_D) was given by: $P_D = 12197 + 4.94P_2 + 688D - 0.1945P_{20}D - 5810\sqrt{D}$, where 20 µm wool is P_{20} cents/kg. Supplements were fed if the body condition of ewes fell to a predetermined level. The supplement fed per ewe each year (S), expressed as metabolisable energy (in MJ) was described by: $S = -602 - 44.1\overline{SR} + 178.5\overline{P} + 8.71\overline{SR}\,\overline{P} + 539\sqrt{\overline{SR}} - 338.5\sqrt{\overline{P}} - 70.8P\sqrt{\overline{SR}}$, where $\overline{SR}$ and $\overline{P}$ represent the mean stocking rate (ewes/ha) and mean P applied annually.

When a current set of costs and prices was applied to these equations, the maximum gross margin for a SR of 7.1 ewes/ha was $AU119/ha with 8.6 kg P/ha applied annually, and $AU262/ha for SR of 18.2 ewes/ha with 17.6 kg P/ha applied annually. If income derived from sheep is maintained constant, intensifying the sheep enterprise from the low to the high SR system would involve increasing sheep numbers by about 17%, but would release about 55% of the farm's area for another purpose.

Additional keywords: phosphate, economics, wool quality, pasture, farming systems.

Introduction

Productive pastoral agriculture in the high rainfall zone (>550 mm rainfall/year) of southern Australia has depended on the use of phosphatic fertilisers, together with subterranean clover (*Trifolium subterraneum* L.) or white clover (*T. repens* L.), and introduced grasses (Bishop 1964; Donald 1964). The potential for increasing productivity of pastures in south-west Victoria is still high (Schroder *et al.* 1992).

Previous Australian research has shown that to derive fully the potential animal production from these 'improved' pastures, the rate of stocking must be sufficient to ensure that the extra pasture is utilised efficiently. Studies by Carter and Day (1970) at Kangaroo Island, and Curll (1977) at Tumbarumba, showed that when pastures were well fertilised, they could support more animals, so that productivity per unit area was increased. Both studies compared a series of fixed stocking rates of ewes in factorial combination with fixed rates of fertiliser. Cannon (1969), who compared the effects of superphosphate applied at 3 rates on the productivity of wethers at a range of 7 stocking rates near Benalla, used a different experimental approach in that not all possible factorial combinations were included. The most lightly stocked

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treatment was fertilised at the lowest rate only, and the most heavily stocked treatment at the highest rate only. This approach excluded the high stocking rate–low fertiliser treatment, where pastures would be over-grazed, and the inefficient low stocking rate–high fertiliser treatment.

An experiment at Hamilton, originally used to compare responses to superphosphate under either mowing or grazing by wethers (Cayley and Hannah 1995), has been used to assess the effects of superphosphate on spring-lambing Merino sheep set-stocked since 1988. Results from this site have shown that most of the response to the fertiliser occurred in spring (Cayley *et al.* 1998). Cayley *et al.* (1998) argued that ewes lambing in spring (15 September) would be more profitable than those lambing in autumn (31 May) if stocked at equivalent stocking rates on these up-graded pastures because more of the pasture grown in spring would be eaten before its quality deteriorated, and less supplement would be required. A wide range of phosphorus (P) status is represented at this site, from very low to sufficiently high to enable the pastures to produce close to their maximum potential (Cayley *et al.* 1998). The concept of using appropriate stocking rates for the various amounts of fertiliser applied (Cannon 1969) was adopted (Saul and Cayley 1992).

This paper summarises the effects, averaged over 9 years, of applying different quantities of fertiliser at a range of stocking rates on the productivity and profitability of the sheep.

Materials and methods

Experimental site

The study was conducted at the Pastoral and Veterinary Institute, Hamilton (37°49′S, 142°04′E, alt. 200 m). The Institute is situated on duplex soils derived from basalt which are typical of much of south-western Victoria. The mean annual rainfall (1962–1997) was 700 mm (standard deviation ≈130 mm) with a winter incidence. The mean monthly rainfalls from 1988 to 1997 were similar to the long-term means for this site (Fig. 1). The experiment was established on pasture

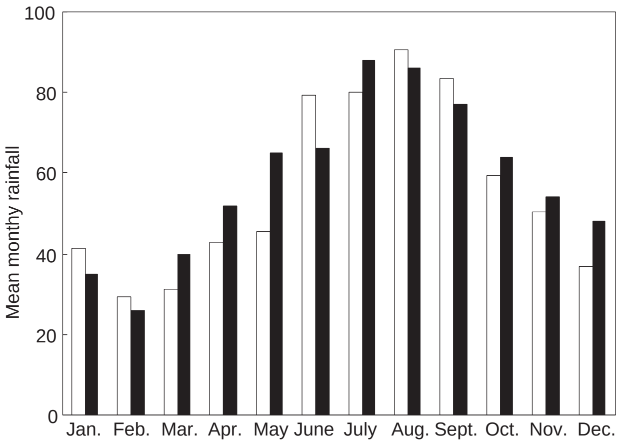

Fig. 1. Mean monthly rainfall 1988–97 (open bars) and long-term means (solid bars).

Table 1. Stocking rates (ewes/ha) at low, medium, and high grazing pressures at six levels of fertiliser from 1988–89 to 1996–97

Mean stocking rates (SR) from 1989 to 1997 have been arranged in four classes (1–4 in parentheses)

Year	Level of fertiliser 1	2	3	4	5	6
			Low grazing pressure			
1988–89	7.50	7.50	8.75	8.75	10.00	10.00
1989–90	7.50	7.50	8.75	10.00	11.25	11.25
1990–91	6.25	7.50	8.75	10.00	11.25	12.50
1991–97	5.00	6.25	8.75	10.00	11.25	12.50
Mean 1989–97 (and SR class)	5.5 (1)	6.6 (1)	8.8 (1)	10.00 (2)	11.3 (3)	12.3 (3)
			Medium grazing pressure			
1988–89	10.50	10.50	12.25	12.25	14.00	14.00
1989–90	10.50	10.50	12.25	14.00	15.75	15.75
1990–91	8.75	10.50	12.25	14.00	15.75	17.50
1991–97	7.00	8.75	12.25	14.00	15.75	17.50
Mean 1989–97 (and SR class)	7.7 (1)	9.2 (2)	12.3 (3)	14.00 (3)	15.8 (4)	17.3 (4)
			High grazing pressure			
1988–89	13.50	13.50	15.75	15.75	18.00	18.00
1989–90	13.50	13.50	15.75	18.00	20.25	20.25
1990–91	11.25	13.50	15.75	18.00	20.25	22.50
1991–97	9.00	11.25	15.75	18.00	20.25	22.50
Mean 1989–97 (and SR class)	9.8 (2)	11.8 (2)	15.8 (4)	18.0 (4)	20.3 (4)	22.2(4)

Average SR (1989–1997) of each SR class			
Class 1	Class 2	Class 3	Class 4
7.11	10.07	12.60	18.21

that was sown in 1977 to a mixture of perennial ryegrass (*Lolium perenne* L.) cv. Victorian, phalaris (*Phalaris aquatica* L.) cv. Australian, and subterranean clover (*Trifolium subterraneum* L.) cvv. Bacchus Marsh and Mount Barker. The pasture species were sown with an oat crop and about 200 kg/ha of single superphosphate. Before sowing the paddock had received no fertiliser. Apart from cultivation, no attempt was made to control the unproductive species such as *Romulea rosea* (L.) Eckl. (onion grass) that were present prior to sowing. In the following year the paddock was grazed with sheep, but not fertilised. The establishment of ryegrass and clovers was reasonable, but the phalaris did not establish well. In 1988, more productive cultivars of subterranean clover were introduced by direct drilling seed of subterranean clover var. y*anninicum* cvv. Trikkala and Larisa (10 kg/ha of each) into all pastures. These cultivars have been shown to be superior to the original clovers sown (Reed *et al.* 1985; Clark *et al.* 1997). To facilitate sowing, all plots were slashed and grazed in rotation with a large mob of sheep to clean up herbage residues. The direct drilling was done without herbicide in order to preserve changes in botanical composition induced by the fertiliser and stocking rate treatments. Further details of the site have been provided by Cayley and Hannah (1995).

Design

A non-replicated factorial design was used. Initially 6 levels of superphosphate in factorial combination with 3 stocking rates (10, 14, or 18 wether hoggets/ha) were allocated in random sequence to 18 plots, each of which was grazed with 8 sheep (Cayley and Hannah 1995). In order to prevent undue stress on animals where levels of fertiliser were low and to ensure that the herbage produced on well-fertilised pastures was utilised, the stocking rate was varied with the amount of fertiliser applied in 1987 (Cayley *et al.* 1998). This was achieved by varying the number of sheep per plot according to the level of fertiliser. This concept was retained when the experimental animals were changed to spring-lambing Merinos in 1988 (Saul and Cayley 1992). Adjustments to the stocking rates were made over a period of a few years (Table 1), with the constraint that the number of sheep grazing the plots at a given level of fertiliser should be the same; for example, from 1991 to 1997, all 3 plots at fertiliser level 1 were grazed with 4 ewes, and the plots at fertiliser levels 2–6 were each grazed with 5, 7, 8, 9, or 10 ewes, respectively. This constraint ensured that the plots at each level of fertiliser were always grazed at a low, medium, or high grazing pressure (Table 1).

Pastures and pasture management

From 1988 up to the present time the plots were continuously grazed throughout the year except for about 5 weeks in autumn during which sheep were amalgamated into larger mobs for mating (see *Animals* below). Pest management was restricted to the occasional need to control black-headed cockchafer (*Aphodius tasmaniae* Hope) larvae with Fastac® [10 g a.i. (alpha-cypermethrin)/10 L water.ha); Cyanamid Agriculture]. Assessments of botanical composition of the pastures were made by hand-sorting of material collected from about 30 'toe cuts' per plot, or by the dry weight rank method ('t Mannetje and Haydock 1963; Tothill *et al.* 1978). The pastures were de-stocked in December 1982 due to drought, and measurements of pastures and sheep were discontinued during 1983 and 1984, as fences were destroyed by wildfire.

Application of fertiliser

The site has been managed in 3 phases (Fig. 2): a 'build-up' phase, a 'run-down' phase, and a 'maintenance' phase. During the build-up phase (1979–84), single superphosphate was applied in amounts up to 100 kg P/ha annually using a modified seed drill in order to ensure uniformity of application. Comparisons of mowing with grazing were made for the first 4 years. Fertiliser was not applied in 1983, the year of the fire, but was applied at 6 amounts from 4 to 40 kg P/ha in 1984. The run-down phase lasted for 3 years (1985–87). During this period the plots were unfertilised, and comparisons of bicarbonate-extractable soil P and a leaf tissue test made (Cayley *et al.* 1987). The 'maintenance phase', during which all treatments except those at the lowest fertiliser level were fertilised with single superphosphate each autumn, commenced in 1988. This paper covers results from this period (1988–97). The average annual amounts of P applied from 1977 to 1997 were 1.6, 4.2, 8.3, 14.5, 22.6, and 32.9 kg P/ha for the 6 levels of fertiliser. The amounts of fertiliser applied each year have been given by Cayley and Kearney (1999).

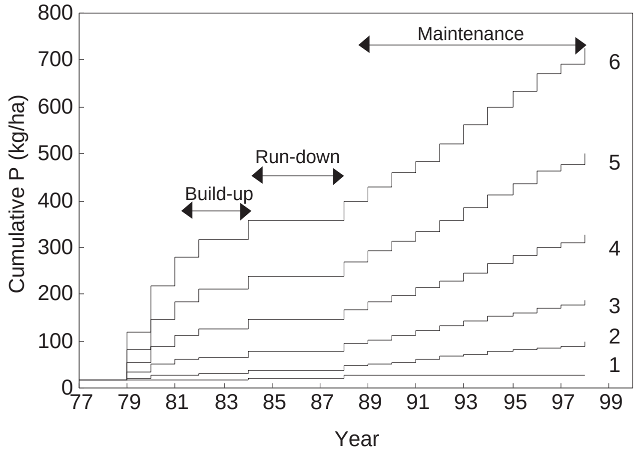

Fig. 2. Cumulative P applied as single superphosphate at six levels during three phases.

Animals

The sheep used for this study were fine-wool Merino ewes, mated in autumn to rams of the same blood-line. The small size of the groups of sheep (4–10 per plot) precluded the assessment of reproductive performance. Ewes (3–6 years old) were mated to lamb in mid September. In early winter, sufficient pregnant animals for the treatments and a group of spares were identified using ultrasound to confirm pregnancy. These sheep were then shorn, weighed, and allocated to the 18 treatments and to a group of spare animals, on the basis of stratified liveweight classes. The ewes were weighed off pasture and their body condition assessed (Jefferies 1961) generally about 1 week after being introduced into their plots and thereafter at regular intervals. Lambs were tagged and weighed at birth and identified to their dams. Ewes whose lambs died were replaced with ewes with single lambs from the spare flock. Those with twins had the smaller lamb removed within 1 week of birth. Animal data for statistical analysis were restricted to animals that had remained on the plots for a full year, and to their lambs. The mean date of birth for individual years, averaged among individual plots, varied from 9 to 30 September, and the average birth date for all treatments and years was 13 September. The lambs were marked and mulesed at about 6 weeks of age, weaned and weighed at an average age of 77 days (average over all years from 1989 to 1997), and removed from the plots. An adjusted weaning weight for each lamb was computed, based on the mean growth rate between birth and weaning for each group, and the birth weight and age at weaning of each lamb. For mating, the sheep were amalgamated into 3 mobs, one for each level of grazing pressure, and the plots corresponding to the 6 levels of fertiliser at each level of grazing pressure were grazed in rotation for 5 weeks.

After the sheep had been on their plots for about 51 weeks, they were weighed and shorn. Fleece and belly wool were weighed, and the annual wool-free change in liveweight computed for ewes that had remained on the plots for the full year. In all years except 1997 a mid-side sample of fleece wool was taken for assessment by the Australian Wool Testing

Authority. Measurements of fibre diameter and yield were made in all years except 1997. Fibre strength was measured in 1989, 1992, 1994, 1995, and 1996; fibre length was measured in 1989, 1992, and 1996. After shearing, the sheep were re-allocated to the treatments using the procedure described above, or new sheep introduced. New sheep were used in 1988, 1989, 1991, 1994, and 1996.

The ewes were drenched with anthelmintics in December and again in February after pastures had dried. Faecal egg counts were made in autumn, and a pre-lambing drench was given if required. In most years only summer drenching was conducted.

Wool price

A data set of wool prices for a range of fine wools (fibre diameter 19–23 µm) from 1987 to 1997 was provided by Graham Lean (pers. comm.). This was used to quantify the relationship between the value of 20 µm wool and the value of other wools corresponding to the range of fibre diameters of fleece wool from this experiment over several seasons.

The relationship between the price of various Merino wools and the corresponding price of wool with a fibre diameter of 20 µm (Fig. 3) is described by Eqn 1:

$$P_D = 12\,197 + 4.94P_{20} + 688\,D - 0.1945P_{20}\,D - 5810\sqrt{D} \qquad (1)$$

where PD represents the price in cents (Australian currency) of a given Merino greasy wool of fibre diameter D µm if the corresponding price of greasy 20 µm Merino wool is P_{20} cents. This model accounted for 98.4% of the variance of P_D and the residual standard deviation (r.s.d.) was 12.8 cents/kg. The disparity in price of the fine and coarser wools in this data set became greater as wool price increased.

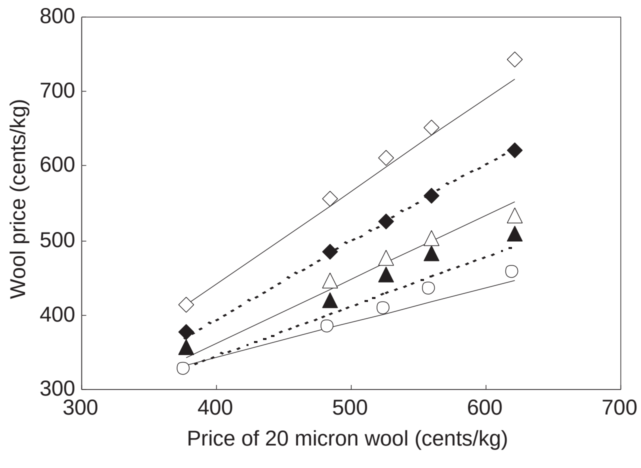

Fig. 3. Association between the price of Merino wools of various fibre diameters and the corresponding price of 20 µm wool. Diameter: 23 µm, ○——; 22 µm, ▲– – –; 21 µm, ∆——; 20 µm, ◆ – – –; 19 µm, ◊———. The lines are fitted to data provided by G. Lean (pers. comm.).

Supplementary feeding

No supplements were fed during the first year that ewes grazed the plots (1988). There were large differences in yearly change in liveweight between the treatments that year. All sheep lost from 1.6 to 10.0 kg for the year because they were heavier than other years when allocated to the treatments. Subsequently, it proved necessary to provide supplementary feed to some of the sheep. Supplementary feeding commenced when a group's mean body condition score (Jefferies 1961) fell to 2.3. A critical score for dry ewes is 2.0 (Caple 1994). Setting a threshold of 2.3 may appear to be somewhat conservative, but when this condition was met at least 1 sheep per group had a condition score of ≤2. By late autumn, when most of this feeding took place, very little of the pasture remained on some treatments. The level of feeding was adjusted so that this level of condition was maintained. In the later years of the experiment, the GrazFeed decision support tool (Freer *et al.* 1997) was used to calculate the level of feeding. Supplements of pasture hay or grain (oats or triticale) were used. These supplements were expressed as metabolisable energy (ME) in order to obtain the mean quantity of supplement fed over years. The ME of the supplements was assessed by the FeedTest fodder testing service which is based at the Pastoral and Veterinary Institute. Supplementary feeding generally took place from January to May, but some groups were also fed in early spring during 1994 and 1996.

Statistical analysis

During 1988, there were large variations in liveweight change of the ewes compared with other years; possibly due to heavier sheep being used that year and also to the pastures settling in after re-sowing. This was also the only year during which no supplements were fed. The 1988 data were thus regarded as atypical and were excluded. Initially, the means for annual animal production variates and supplement fed from 1989 to 1997 were computed. For most statistical analyses, the stocking rates from 1989 to 1997 were arranged in 4 classes: 1, 2, 3, and 4 (Table 1). The average stocking rates were 7.11, 10.07, 12.60, and 18.2 ewes/ha for classes 1–4, respectively.

The general approach we adopted was to use non-linear regression to model the average annual animal production per head (y) in terms of the average annual amount of P applied per hectare (annual P) by fitting exponential curves of the form:

$$y = A - BC^{\text{annual P}} \qquad (2)$$

In this model A is the value of y at the asymptote, B is the range in y between annual P = 0 and the asymptote, and C is the rate of exponential increase or decrease in y. This approach was used for wool produced per ewe, annual liveweight change of ewes, and birth and weaning weight of lambs.

The amount of supplement fed and wool strength were modelled by multiple linear regression using stocking rate (SR), annual P, the square roots of SR and annual P, and interaction terms derived from these variates as terms. These terms have no biological counterparts, but were used to derive a predictive equation (see Eqn 4) that fitted the data at hand. A similar approach was used to derive a function (Eqn 1), from the set of data provided by G. Lean (pers. comm.), in order to express the price of wool of varying fibre diameter in terms of a standard wool price (the price of 20 µm wool). In all cases, terms were included only if statistically significant ($P<0.05$), and residuals were assessed visually for heterogeneity of variance. The effect of treatments on lamb deaths between birth and weaning was assessed by fitting a generalised linear model with logit link (Collet 1991) for the comparison of binomial proportions. All analyses were undertaken using the GENSTAT for Windows 5.4, software (GENSTAT 5 Committee 1994).

Results

Botanical composition of pastures

The botanical composition of all treatments in late October 1997 (Table 2) shows the sensitivity of onion grass, subterranean clover, the sown perennial grasses, and capeweed [*Arctotheca calendula* (L.) Levyns] to changes in grazing pressure and inputs of superphosphate. An earlier assessment of botanical composition in 1992 showed similar trends.

Table 2. Botanical composition (% dry matter basis) of treatments in late October 1997

Component	Level of fertiliser					
	1	2	3	4	5	6
	Low grazing pressure					
Onion grass	53	34	7	0	0	0
Clover	7	18	41	36	47	25
Capeweed	0	4	4	0	3	0
Sown perennial grass	7	4	25	25	28	53
	Medium grazing pressure					
Onion grass	65	50	4	0	0	0
Clover	1	26	39	39	19	38
Capeweed	0	2	6	0	13	1
Sown perennial grass	1	8	28	42	31	49
	High grazing pressure					
Onion grass	56	41	3	0	0	0
Clover	7	15	24	20	29	15
Capeweed	5	2	1	17	13	53
Sown perennial grass	4	16	40	37	17	13

Animal production

The average animal production per head, and annual changes in liveweight of the ewes, are given in Table 3. Analysis of variance revealed that the A coefficient varied with level of stocking rate for all variables except birth weight. Consequently, a separate A coefficient was estimated for each level of stocking for fleece weight, adjusted weaning weight, and annual change in liveweight. A single A coefficient was used for birth weight. The coefficients B and C did not vary with stocking rate, so common B and C coefficients were used for each stocking rate class. The influences of the single superphosphate on animal production at the 4 classes of stocking rate (Table 4, Fig. 4) mostly show a similar form. All variables except birth weight were influenced by stocking rate as well as the fertiliser. It was not possible to detect any effect of fertiliser on the number of lambs that died between birth and weaning. However, by combining data over years into groups it was possible to show that a greater proportion of lambs (19%) died from the class with the heaviest stocking rate compared with the other classes (mean for classes 1, 2, and 3 combined =13%; $P < 0.05$).

Wool quality

The combined effects of fertiliser and stocking rate on wool quality (Table 5) varied. Fibre diameter varied with fertiliser in a similar way to fleece weight. This trait was not modelled because fibre diameter and fleece weight were correlated. The rate of increase in fibre diameter with increasing greasy fleece weight varied between years from 1.065 to 2.55 μm/kg wool. The relationship, averaged from 1990 to 1996, is given in Eqn 3 and Fig. 5:

Table 3. Mean annual production and supplement fed per ewe from 1989 to 1997 at six levels of superphosphate in combination with three levels of grazing pressure

Stocking rates (SR) from 1989 to 1997 have been arranged in four classes (1–4 in parentheses). The mean SRs were 7.11, 10.07, 12.60, and 18.21 ewes/ha for SR classes 1–4, respectively

Grazing pressure	Level of P fertiliser					
	1	2	3	4	5	6
	Greasy fleece weight (kg), and SR class					
Low	4.02 (1)	4.46 (1)	4.70 (1)	4.66 (2)	4.72 (3)	4.87 (3)
Medium	3.66 (1)	4.25 (2)	4.57 (3)	4.61 (3)	4.51 (4)	4.67 (4)
High	3.80 (2)	3.73 (2)	4.15 (4)	4.15 (4)	4.32 (4)	4.39 (4)
	Weaning weight (kg), and SR class					
Low	18.6 (1)	20.3 (1)	21.5 (1)	22.6 (2)	21.8 (3)	21.6 (3)
Medium	16.2 (1)	19.9 (2)	20.7 (3)	20.6 (3)	20.8 (4)	21.1 (4)
High	16.4 (2)	17.4 (2)	18.4 (4)	20.7 (4)	21.7 (4)	20.8 (4)
	Birth weight of lambs (kg), and SR class					
Low	4.34 (1)	4.45 (1)	4.53 (1)	4.54 (2)	4.68 (3)	4.69 (3)
Medium	4.29 (1)	4.53 (2)	4.67 (3)	4.63 (3)	4.75 (4)	4.44 (4)
High	4.36 (2)	4.23 (2)	4.34 (4)	4.67 (4)	4.57 (4)	4.64 (4)
	Weight-change of ewes (kg), and SR class					
Low	1.7 (1)	3.3 (1)	4.4 (1)	6.2 (2)	4.7 (3)	4.9 (3)
Medium	0.4 (1)	1.8 (2)	3.4 (3)	2.7 (3)	3.5 (4)	5.6 (4)
High	–0.1 (2)	–0.8 (2)	–1.7 (4)	1.5 (4)	2.8 (4)	1.0 (4)
	Supplement fed expressed as metabolisable energy (MJ/ewe)					
Low	81	45	0	0	0	0
Medium	267	43	28	44	38	75
High	333	232	189	119	114	315

$$\overline{D} = 14.18 + 1.48\,\overline{GW} \quad (3)$$

Here, $\overline{GW}$ represents the mean fleece weight (kg) and ($\overline{D}$) the mean fibre diameter (μm). This relationship accounted for 80% of the variance, and the r.s.d. was 0.28 μm. Fibre length was unaffected by treatment (mean 90.3 mm, s.e. 1.16 mm), yield was depressed to a small degree as stocking rate increased, and wool strength appeared to be influenced by both level of fertiliser and stocking rate to some degree. Wool strength was satisfactory in all cases except for the treatment receiving the most fertiliser and stocked at the highest stocking rate (Table 5). The wool for this treatment would be classified as 'tender' (31.4 N/ktex) and would attract a price penalty. It was not possible to fit exponential models to these data. An attempt was made to fit regression models derived from multiple linear regression, but the fit of these models was poor (Fig. 6).

Table 4. Coefficients (±s.e.) of exponential models $y = A - BC^{\text{annual P}}$ that predict animal production in kg per sheep (y) at four classes of stocking rate (1, 2, 3, 4) in terms of the mean amount of single superphosphate applied per year from 1977 to 1997 expressed as kg P/ha (annual P)

Units of coefficients: A and B, kg; C, $\text{kg}^{\text{kg P}}$. Mean stocking rates (SR) from 1989 to 1997 were 7.1, 10.1, 12.6, and 18.2 ewes/ha for SR classes 1–4 respectively. LW, liveweight

Coefficient (SR class)	Annual greasy wool	Adjusted weaning weight	Annual LW change of ewes	Birth weight of lambs
A (1)	5.06±0.157	23.5±0.70	8.32±1.45	
A (2)	4.89±0.124	22.7±0.55	7.01±1.26	
A (3)	4.78±0.122	21.5±0.54	5.36±1.24	
A (4)	4.46±0.084	20.9±0.37	3.38±0.98	
A (1–4)				4.64±0.054
B	1.59±0.221	8.4±1.10	8.52±1.49	0.41±0.104
C	0.84±0.038	0.82± 0.039	0.901±0.038	0.856±0.082
	Variance accounted for (%)[A]			
	78.5	82.2	63.2	51.3

[A]Adjusted R^2.

Supplementary feeding

The mean amount of supplement fed annually to each ewe expressed as ME (MJ/ewe) is described by Eqn 4:

$$\text{Supplement} = -602 - 44.1\overline{SR} + 178.5\overline{P} + 8.71\overline{SR}\,\overline{P} + 539\sqrt{\overline{SR}} - 338.5\sqrt{\overline{P}} - 70.8\overline{P}\sqrt{\overline{SR}} \quad (4)$$

Here $\overline{SR}$ and $\overline{P}$ refer to the mean stocking rate (ewes/ha) and mean P applied annually (kg/ha) from 1989 to 1997. This model accounted for 86.3% of the variance in mean supplement fed, and the r.s.d. was 37.2 MJ/ewe.year.

The fit of the model to the data is shown in Fig. 7*a*, and the predicted amount of supplement fed per year as a response surface (Fig. 7*b*). Most of the supplement was fed to sheep grazing pastures that received very small amounts of fertiliser. For stocking rates of up to about 12 ewes/ha, supplement was not required if more than 13 kg P/ha.year had been applied, but at higher stocking rates, more supplementary feeding was required despite heavy applications of fertiliser.

Table 5. Influence of level of fertiliser and stocking rate on wool quality

Grazing pressure	Level of superphosphate 1	2	3	4	5	6
	Stocking rate (ewes/ha)					
Low	5.5	6.6	8.8	10.0	11.8	12.3
Medium	7.7	9.2	12.3	14.0	15.8	17.3
High	9.8	11.8	15.8	18.0	20.3	22.2
	Yield (%)					
Low	76.5	77.0	76.7	76.7	76.6	76.5
Medium	75.0	77.7	76.8	76.5	76.4	76.6
High	76.3	75.8	74.8	76.6	74.7	73.9
	Fibre length (mm)					
Low	92.4	88.8	92.0	97.9	79.1	90.6
Medium	81.6	92.6	95.2	94.2	91.3	96.4
High	92.1	84.4	91.3	86.9	91.6	87.3
	Fibre diameter (μm)					
Low	19.9	21.2	21.2	21.0	21.3	21.4
Medium	19.1	20.2	21.1	21.1	20.7	21.3
High	20.1	20.5	20.3	20.3	20.5	20.3
	Fibre strength (N/ktex)					
Low	41.4	54.6	51.4	52.3	51.2	52.7
Medium	38.4	53.4	55.0	53.4	50.4	55.1
High	43.4	49.4	42.8	52.0	42.3	31.4

Profitability

The influence of single superphosphate on the productivity of the sheep systems at the 4 levels of stocking rate class was assessed using Eqn 2 to predict greasy wool production per ewe and weaning weight of the lambs. When multiplied by the mean stocking rate for each stocking rate class, these values give production per unit area. Eqn 3 was used to predict the fibre diameter of the wool and Eqn 1 to predict the price of this wool for a given value of 20 μm wool. Penalties for tender wool were ignored for the stocking rate class 4, as only the wool from the most heavily stocked plot at the highest level of fertiliser was tender (Table 5) and the stocking rate of the sheep here was far higher than the average stocking rate of class 4. The amount of supplement required was predicted using Eqn 4. For this purpose fitted values of less than zero were regarded as zero.

These equations were embedded in a computer spreadsheet in order to assess the effect of varying average amounts of P applied as superphosphate on the production of lambs and wool, and hence profitability (Fig. 8). The gross margin at each stocking rate class was computed for an assumed set of costs (variable costs of ewes, superphosphate, and supplement) and values of output (price of 20 μm wool and value of

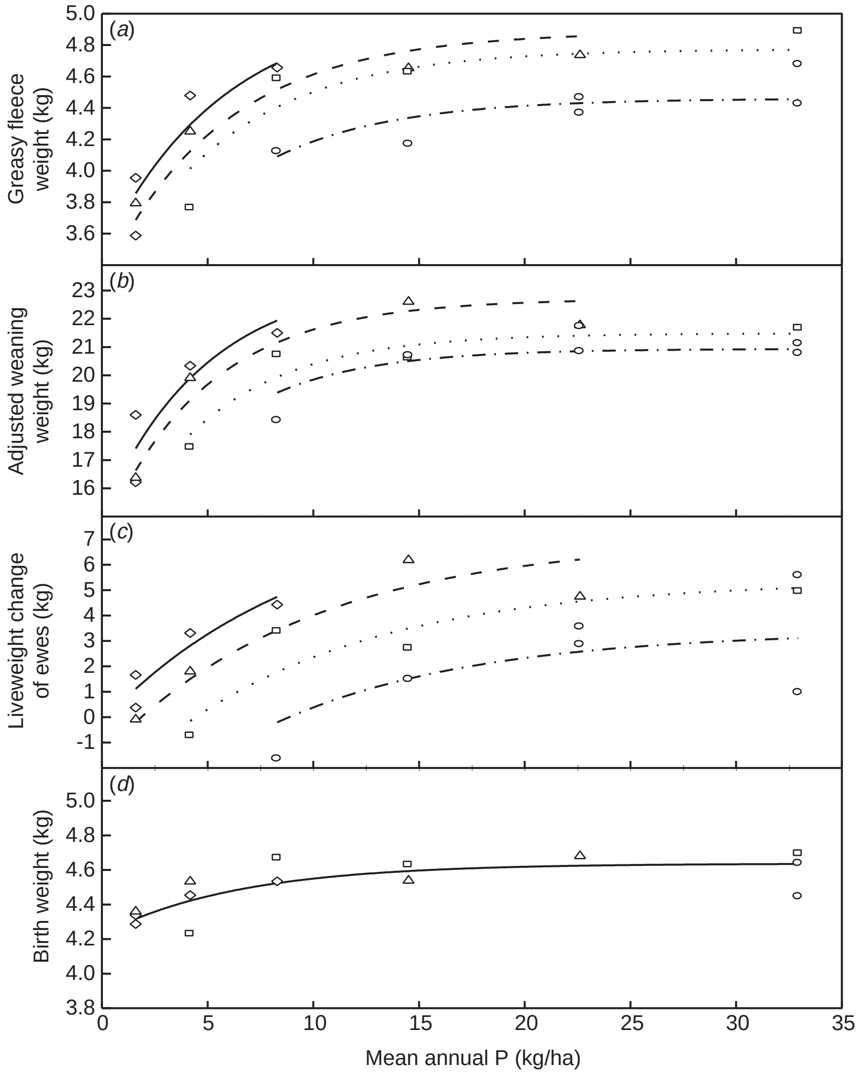

Fig. 4. Effect of fertiliser at 4 levels of stocking rate (SR) on (*a*) annual wool produced per ewe, (*b*) weaning weight of lambs, (*c*) annual liveweight change of ewes, and (*d*) birth weight of lambs. Mean SRs (ewes/ha): 7.11, ◊ ——; 10.07, Δ – – – : 12.60, □ ·····; 18.21, ○ – · –.

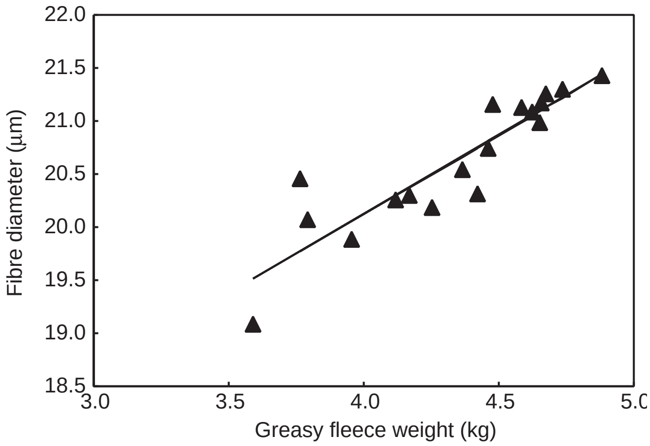

Fig. 5. Association between fibre diameter and fleece weight (data points are mean values from 1989 to 1997 of all treatments).

lambs). Lamb mortality between birth and weaning was assumed to be 15%. For simplicity, possible benefits or penalties associated with the annual liveweight changes of the ewes were ignored. The maximum gross margin for stocking rates of 7.1, 10.1, 12.6, or 18.2 ewes/ha were \$119, \$172, \$203, and \$262, respectively.

We have considered 2 ways to determine the precision of these estimates of gross margin. It would be possible, in principle, to fit nonlinear equations simultaneously and estimate the variance and covariance of gross margins derived from the sale of wool and lambs. The variance and covariance could then be used to construct the confidence region for the combined gross margins based on the simultaneous fitting of the nonlinear equations. The region generated is an ellipsoid. A simpler approach, although with an assumption of no covariance, is based on the individual confidence intervals

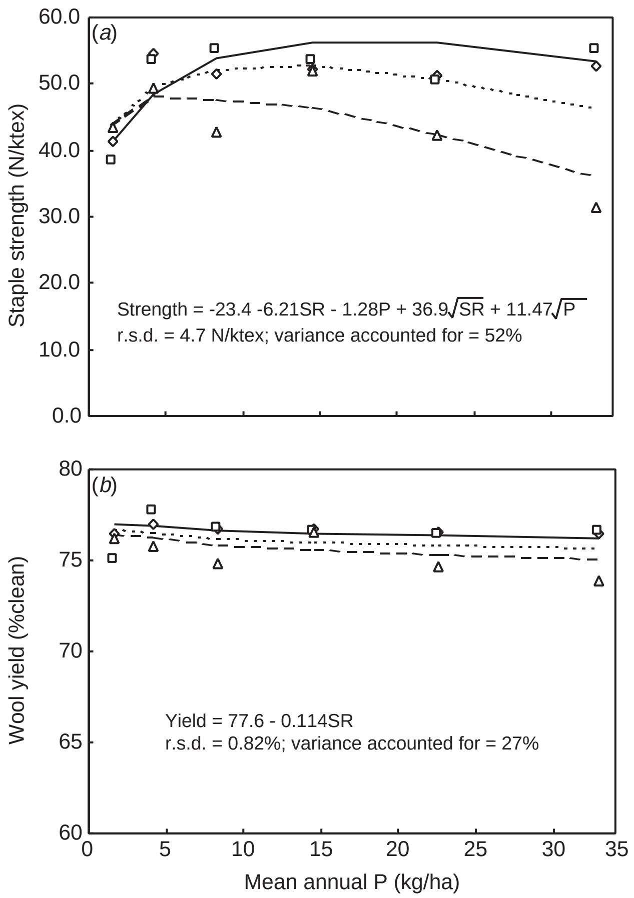

Fig. 6. (*a*) Effect of fertiliser and stocking rate (SR, units: ewes/ha) on wool strength, and (*b*) effect of SR alone on wool yield. Data and fitted lines correspond to 3 levels of grazing pressure (see text): low, ◊ ——; medium, □ ········; high, Δ – – – –.

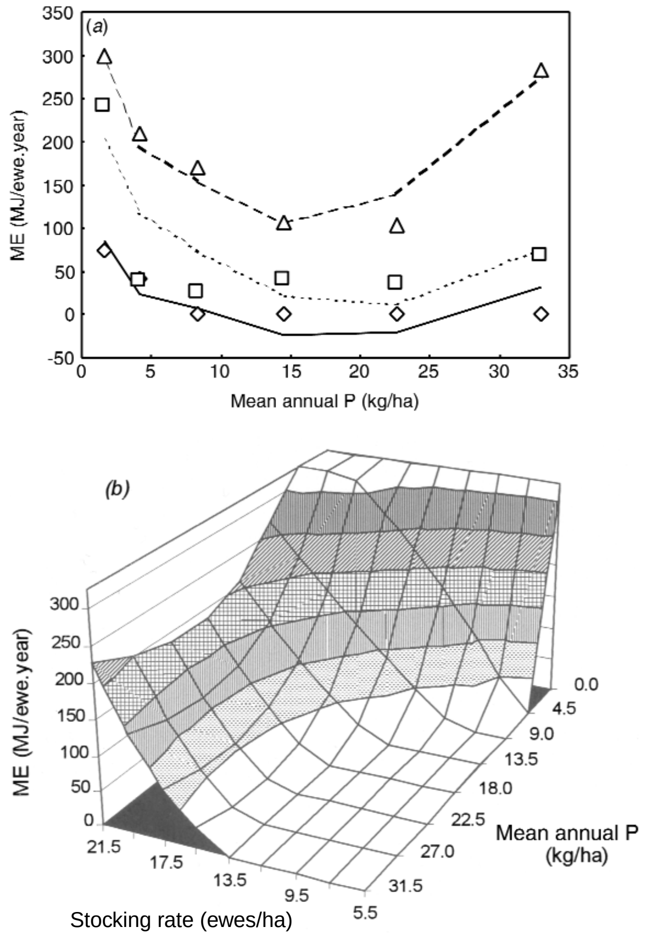

Fig. 7. Association between stocking rate (SR), applied P, and supplements expressed as metabolisable energy (ME) fed to ewes. (*a*) Data and fitted values at 3 levels of grazing pressure (see text): low, ◊ ——; medium, □ ········; high, Δ – – – –. (*b*) Surface showing association between SR and fertiliser on supplement fed. 'Contour interval': 50 MJ/ewe.year.

for the predicted responses to P of adjusted weaning weight and wool produced per ewe. The extreme points, i.e. the upper and lower bounds, can be used to give a confidence interval for the model as a whole. This approach is conservative because the extreme points would be outside the ellipsoid confidence region generated by fitting the equations simultaneously.

Upper and lower 95% confidence limits for predicted gross margins of the 10.1 and 18.2 ewes/ha groups are given in Fig. 9. These limits were calculated using the second procedure, but still show good separation of the predictions, especially where the average amounts of fertiliser applied approach quantities sufficient to give maximum predicted profits.

Discussion

Experimental approach

A problem associated with increasing stocking rates to match pasture production is that production per sheep at a given grazing pressure might fall if the stocking rates chosen are too high. If this occurs, difficulties in interpretation will be experienced if results are expressed in terms of production per unit area, as fertiliser and stocking rate are confounded. Production per sheep rather than production per unit area was therefore used as the ***y*** variate. We were mostly successful in adjusting stocking rate to match pasture produced (Table 3). However, in 1988–89 when no supplements were fed, fleece weight and weaning weight of lambs were depressed on the high P–high grazing pressure treatment (data not presented here). Data from this year were not included in calculating the mean values used in the statistical analyses. There is, however, a considerable benefit in using the approach we adopted, because when pasture production is matched with an appropriate stocking rate, it enables an estimate of the potential productivity of the pastures to be made (Saul and Cayley 1992). This may not always be possible if a rigid

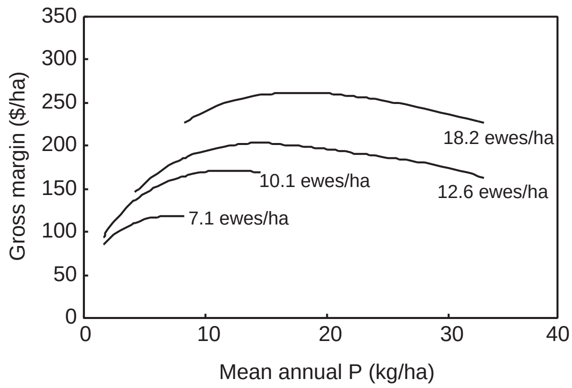

Fig. 8. The effect of various average annual applications of single superphosphate (as P) on predicted gross margins of spring-lambing Merinos at 4 stocking rates. Assumptions: lambs weaned = 85% of ewes mated; 20 µm wool, 400 cents/kg greasy; superphosphate, $200/t; lambs, $0.75/kg liveweight; oats, $150/t; and variable costs, $11.50/ewe.

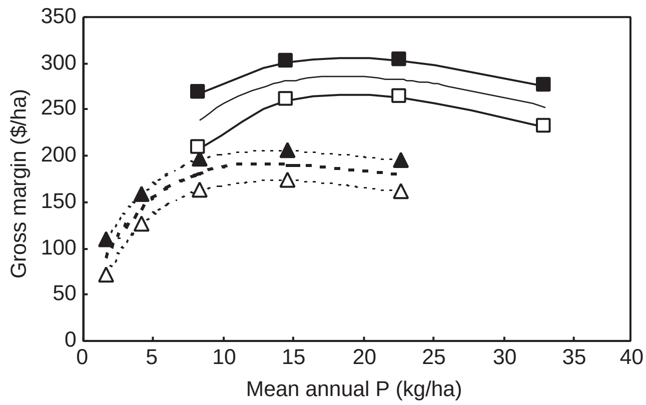

Fig. 9. Upper and lower 95% confidence limits for predicted gross margins of spring-lambing Merino ewes stocked at 10.1 or 18.2 ewes/ha, and grazing pastures fertilised with varying annual amounts of superphosphate (as P): 18.2 ewes/ha ——, ■ (upper), □ (lower); 10.1 ewes/ha – – –, ▲ (upper), △ (lower).

experimental design with fixed stocking rates for all levels of fertiliser is employed.

Two methods may be used to assess the most profitable combination of stocking rate and fertiliser from this experiment. The first is to calculate the stocking rate that results in the most profit for each of the 6 fertiliser levels (Cayley and Saul 1993), and the second is to examine the relationship between the amount of fertiliser applied and gross margin at a series of fixed stocking rates. We contend that the second approach is more useful because stock numbers are generally maintained close to a constant level. In order to establish these relationships, the response to fertiliser at a range of stocking rates is required. For this to be calculated, it was necessary to amalgamate treatments with similar stocking rates into separate classes. It is not possible to predict response to fertiliser at a specific stocking rate with the approach we have adopted, and interpolation has to be used; however, the range in stocking rates of the 4 stocking rate classes is likely to more than cover the full range in stocking rates in southern Australia for areas of similar rainfall.

The studies by Cannon (1969), Carter and Day (1970), and Curll (1977) were for 3 years and were undertaken on pasture land where some superphosphate had been applied in the past. In each case, the differences in production between treatments receiving the most and least fertiliser became progressively greater with time. If these differences were subsequently maintained, averaging the effects of fertiliser over 3 years would underestimate differences between fertiliser treatments over the long term. This problem was minimised in our study, where assessments commenced 10 years after the treatments were imposed.

Criteria for supplementary feeding

The botanical composition of pasture receiving the most fertiliser and stocked at the highest rate (plot 15) differed from other plots receiving the heaviest applications of fertiliser. Compared to other plots, plot 15 was dominated by annual species (Table 2) which consistently failed to support the animals throughout the summer. Considerable amounts of supplement had to be fed to the sheep on this treatment (Table 3) but, despite this, the actual annual liveweight change of the ewes here was less than the predicted value (Fig. 4*c*). The decision to use body condition alone for deciding when to feed a supplement may also have led to the deterioration of this plot's pasture. Criteria for supplementation based on the condition of the pastures, similar to that used to make decisions about de-stocking (Morley and Daniel 1992), may have been more appropriate in this case.

Wool

The increased wool production per ewe associated with larger amounts of superphosphate being applied was due mainly to increased fibre diameter, and there was a significant correlation between fibre diameter and fleece weight. Staple length was unaffected by fertiliser and stocking rate treatments and the effect of treatments on clean scoured yield was small. We can only speculate that the decrease in yield associated with increasing stocking rate was due to an increase in dust, but this relationship was too poor to use in the spread sheet. There is concern that, with improved nutrition, fibre diameter could increase at a rate that will negate any benefit due to increased production per sheep. Inspection of Fig. 3 suggests that this problem is more likely to arise if the wool price is high, in which case it would be appropriate to operate at a higher stocking rate in any case.

The association between increase in fleece weight and corresponding increase in fibre diameter following improved nutrition is reputed to vary among strains of Merinos, but our experiences, and those of White and McConchie (1976), show that year-to-year variation can also be large. In our case there were no consistent patterns due to seasonal rainfall, or to the source and age of the sheep. White and McConchie (1976) assessed the relationship between fibre diameter and fleece weight for Merino wethers, where the wool was coarser (fibre diameter 20–26 μm), and staple length longer (about 90–110 mm). For a given fibre diameter, these wethers produced about 1 kg more wool per sheep than our ewes.

Poor wool strength was only a problem with wool from plot 15. The sound wool from the other treatments was probably due to shearing the sheep in late autumn–early winter, which eliminates the weakest point of the staple. It is likely that the tender wool from plot 15 was associated with the loss of body condition following the depletion of pastures in late summer, and the change to a maintenance diet of grain, a situation that should be anticipated if a wool grower intends to intensify production.

Lamb deaths

The overall lamb mortality between birth and weaning of about 16% is consistent for Merinos lambing in an exposed situation at Hamilton (Egan *et al.* 1972). Our finding that a higher proportion of lambs died in the heaviest stocking rate class is consistent with results reported by Lloyd Davies (1964, 1968), Egan *et al.* (1977), and Lloyd Davies and Southey (1985). Lloyd Davies (1987) speculated that this may be due to the sheltering effect of the more abundant herbage present at low stocking rates. Lamb mortality is closely related to shelter (Egan *et al*. 1972), which will clearly vary from site to site, so results from our study were not included in the spreadsheet model.

Profitability

The results show that the stocking rate must be increased in order to derive the potential benefits from fertilised pastures. At the levels of costs and prices chosen (Fig. 8), it was necessary to apply about 1 kg of P/ha for each ewe per ha in order to make the most profit at a given stocking rate. The curves generated from the spreadsheet assume 85% of lambs weaned per ewe mated. This is consistent with expected weaning percentages from ewes lambing in an exposed site (Egan *et al.* 1972, 1977). Neonatal mortality of lambs is site-dependant, so in the spreadsheet, this variate can be altered to suit each case.

Our estimates of the effects of fertiliser on profitability were conservative, for a number of reasons. Some transfer of nutrients between plots would occur due to the mating procedure; however, P levels in faeces at this time of year are lower than when the pastures are green (Bromfield 1961). The small amount of nutrients transferred between plots at this time may have slightly reduced differences between plots receiving different amounts of fertiliser. We were also unable to assess cumulative effects of treatments on subsequent animal production because the sheep were re-allocated each year. Differences in lamb production may have been greater if the sheep remained on the plots for more than one year, as poor nutrition may have led to reduced conception rates and survival rates. The birth weight of lambs was influenced by fertiliser but not by stocking rate. Differences due to stocking rates may have occurred if animals had remained on plots for successive years. Similarly, we ignored the annual liveweight change of the ewes in our spreadsheet. This change may also be influenced by previous treatment on the occasions the sheep were re-allocated, making it difficult to use this information for little more than a general guide to the nutrition of the sheep. Morley *et al.* (1978) estimated that the lambing percentage will be increased by about 1.75% for every extra kg of ewe liveweight at mating. In addition, heavier ewes would attract a higher price when they were sold. A final reason for our conservative estimate of fertiliser on profitability was that the stocking rate class 4 (mean stocking rate 18.2 ewes/ha) included the most heavily stocked (22.2 ewes/ha) and heavily fertilised plot. This plot also required large amounts of supplement (Table 3, Fig. 7*a*). The inclusion of these data in the mean for stocking rate class 4 overestimates the amount of supplement required by 18.2 ewes/ha at the highest level of fertiliser.

Applicability of results

The Grassland Society of Victoria's Grasslands Productivity Program (de Fegely 1997) shows that intensification of pastoral agriculture based on the efficient utilisation of well-managed pastures is widely applicable in southern Australia's high rainfall zone. The Program involved about 200 producers from southern New South Wales, Victoria, South Australia, and Tasmania, each of whom compared the profitability of an 'up-graded' paddock (more fertiliser and increased stocking rate) with a 'standard' paddock. Schroder *et al*. (1992) showed that while the potential productivity of pastures in south-western Victoria was about 95 kg wool/ha.year, the mean production derived from a survey of farms was 44 kg wool/ha.year and this had not changed for 20 years.

Clearly there are significant barriers to adoption of this technology. Major constraints are the difficulty of increasing the amount of fertiliser and numbers of sheep when commodity prices are low, and the likelihood of extra work associated with running more animals on the farm. A further perceived problem is that increasing the stocking rate may exacerbate problems with internal parasites, but experience with the Grasslands Productivity Program shows that this latter concern may be without foundation where the stocking rate is increased on better quality pastures. In addition, Saul (1996) reported reduced counts of parasitic nematode eggs in faeces of sheep grazing 'upgraded' pastures at a stocking rate that was 50% higher than 'standard' pastures.

The potential to intensify livestock production leads to the notion of releasing part of the farm's area for another purpose, while retaining either the same number of sheep or the same income derived from them. Using the assumptions in Fig. 8, it can be shown that the maximum predicted gross margin for a stocking rate of 7.1 ewes/ha would be $119/ha if 8.6 kg P/ha were applied annually, and $262/ha for a stocking rate of 18.2 ewes/ha with 17.6 kg P/ha applied annually. For income derived from sheep to remain unchanged, intensifying the sheep enterprise from the low to the high system would involve increasing sheep numbers by about 17%, but would release about 55% of the farm's area for another purpose. If sheep numbers are retained, the gross margin derived from sheep averaged over the whole farm will fall to $102/ha if the sheep enterprise is intensified, but only 39% of the farm's area will be required for the sheep. One use to which land released from grazing could be put is farm forestry, either for small-scale specialty timber (Bird 1997) or for pulp wood production. Leases paid for land for plantations of blue gums (*Eucalyptus globulus* Labil.), which are grown to produce wood pulp, currently exceed operating returns for wool or beef attainable from average pastures in south-western Victoria (A. Patterson pers. comm.). An additional benefit is that from the second year onwards, these wood lots and plantations may be used to provide shelter for livestock during periods of bad weather (Bird and Cayley 1991). Another land use may be cropping. Current work at Hamilton (P. Riffken pers. comm.) is investigating novel crop rotations based on alternate years of subterranean clover or other forage legumes (Craig *et al.* 1998; Evans and Cameron 1998) and cereals. The degree to which various portions of a farm can be released for other purposes will depend on the current stocking rate, the area of soil suitable for the other enterprise, risks associated with the new enterprise, and attitudes towards managing the sheep more intensively. Risks associated with the sheep have to some extent been accounted for in this long-term study, where the annual rainfall varied from 501 to 869 mm.

Often the conclusion drawn from projects like this is that production can be increased by a certain degree. A more acceptable application of these findings may be to use them to plan how to diversify the farm business.

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