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Figure 2 contains some incorrect values and is reproduced correctly below.

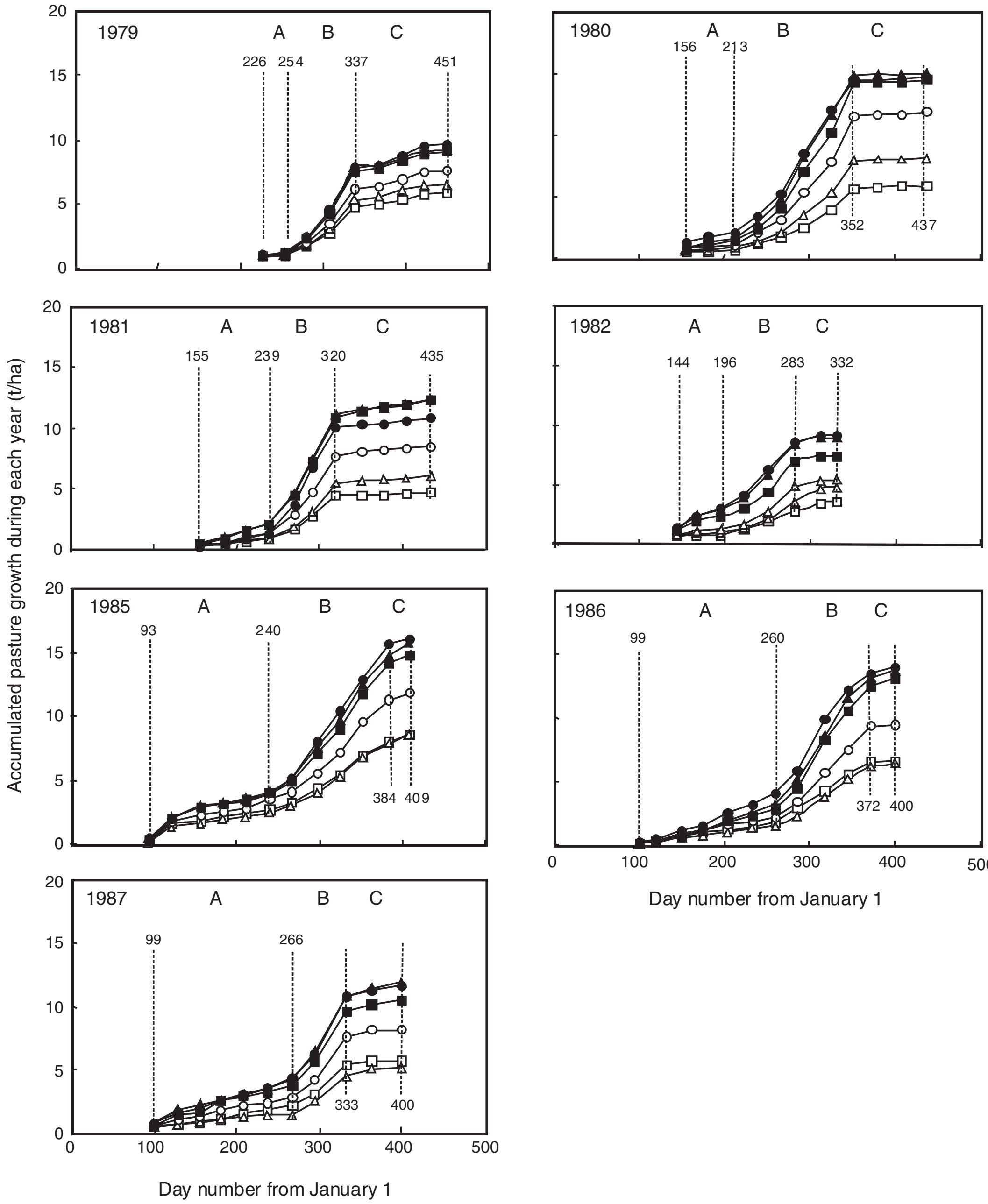

Fig. 2. Cumulative production of pasture (t DM/ha) for each year. Periods marked A, B and C correspond to different phases of pasture growth, designated as 'winter', 'spring', and 'summer' respectively. The day number from the start of each year corresponding to the beginning and end of each phase is also given. P level: 1 □, 2 △, 3 ○, 4 ■, 5 ▲, 6 ●.

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Effects of phosphorus fertiliser and rate of stocking on the seasonal pasture production of perennial ryegrass–subterranean clover pasture

J. W. D. Cayley[AC], *M. C. Hannah*[B], *G. A. Kearney*[A], *and S. G. Clark*[A]

[A] Agriculture Victoria Hamilton, Pastoral and Veterinary Institute, Private Bag 105, Hamilton, Vic. 3300, Australia.
[B] Agriculture Victoria Ellinbank, Dairy Research Institute, RMB 2460 Hazeldean Road, Warragul, Vic. 3820, Australia.
[C] Corresponding author; email: cayleyj@hammy.agvic.gov.au

Abstract. The response of pastures based on *Lolium perenne* L. and *Trifolium subterraneum* L. to single superphosphate was assessed at Hamilton, Victoria, by measuring the growth of pastures during winter, spring, and summer over 7 years from 1979 to 1987. The seasons were defined by the pattern of pasture production, rather than by calendar months. Winter was the period of constant growth rate following the autumn rain; spring was the period of accelerating growth rate until growth rate changed abruptly following the onset of dry summer weather. Pastures were grazed with sheep at a low, medium, or high grazing pressure, corresponding generally to stocking rates of 10, 14, or 18 sheep/ha. At each level of grazing pressure, single superphosphate was applied at 5 rates from 1979 to 1982; the highest rate, expressed as elemental phosphorus (P), was reduced from 100 to 40 kg/ha during this time. In addition there was an unfertilised treatment. In 1984, fertiliser was applied at 6 rates from 4 to 40 kg P/ha. No fertiliser was applied in the remaining years, including 1983. Pasture production was measured from 1979 to 1982 and from 1985 to 1987.

Total pasture dry matter (DM) accumulation per year at the highest stocking rate was less than the other treatments in 4 of the years. Averaged over all years and fertiliser treatments, the annual net production was 10·1, 10·1, and 9·0 t DM/ha ($P < 0 \cdot 05$) for plots grazed at low, medium, and high stocking rates, respectively. The amount of fertiliser required to reach a given proportion of maximum yield response did not vary between winter and spring in any year, but the greater potential yield in spring ($P < 0 \cdot 001$) meant that as more fertiliser was applied, the disparity between pasture grown in winter and pasture grown in spring increased. Differences in this disparity between extreme levels of P ranged from 1·4 t DM/ha in a drought to about 7 t DM/ha in a good season.

The implications for managing farms when pastures are fertilised at higher rates than currently practised by district farmers are that systems of animal production with a requirement for plentiful good quality pasture in spring, such as ewes lambing in spring, should be used. The benefit of spring lambing over autumn lambing was supported when the 2 systems were compared over 26 years using the GrassGro decision support system. Well fertilised pasture systems will also allow more scope for conserving pasture as hay or silage, and increase opportunities for diversification in the farming enterprise, such as spring-growing crops.

Additional keywords: phosphate, sheep, simulation, GrassGro.

Introduction

The use of single superphosphate for pastures in Australia is widespread (Donald 1964; Lazenby 1976). The fertiliser has been applied to pastures in south-western Victoria on a regular basis for longer than in other areas in Australia (Bishop 1964). Applications of superphosphate result in increases in pasture production (Cameron and McGowan 1969; Curll 1977; Garden *et al*. 1978; McGowan *et al*. 1983; Jones *et al*. 1984;

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Gardener *et al.* 1993; Jones and Betteridge 1994), and changes in botanical composition (Rossiter 1964; Cook *et al.* 1978; Shaw 1978), mineral content and quality (Ozanne and Howes 1971; Thornton and Minson 1973; Hendricksen *et al.* 1992; Jones and Betteridge 1994), and intake (Ozanne and Howes 1971; Ozanne *et al.* 1976; Coates 1995).

Given that the increases in pasture productivity associated with heavier applications of phosphatic fertilisers are not associated with decreases in quality, an increase in total pasture production implies that a corresponding increase in animal production can be achieved, by increasing either production per head or the rate of stocking or both. The most likely way of ensuring that the extra pasture produced is utilised is to increase the stocking rate (Carter and Day 1971; Cannon 1972; Curll 1977; Winter *et al.* 1989; Gardener *et al.* 1993). The extent to which this can be done will depend on the capability of the fertilised system to provide enough forage of sufficient quality to meet the seasonal requirements of the animals.

Reports on the seasonal response of pasture to superphosphate in temperate Australia vary. Three studies have been conducted at Rutherglen, Victoria. Cameron and McGowan (1969) reported that absolute responses were greater during winter than spring. McGowan and Cameron (1972) showed that responses to fertiliser during winter or spring were influenced by the time of application of fertiliser. Subsequently, McGowan *et al.* (1983) showed that whereas response during winter was influenced by initial and subsequent applications of fertiliser, when averaged over 4 years, response during spring was the same whether fertiliser was applied as a single dressing in one year or as smaller applications spread over the next 3 years. The magnitude of responses in spring and winter were similar.

In New South Wales, Curll (1977) showed that at Tumbarumba, where the rainfall does not exhibit a strong winter-incidence, seasonal responses to superphosphate varied between years. Cook *et al.* (1978) reported negligible growth (and response to superphosphate) in winter at Armidale. In the USA, Robinson *et al.* (1959) demonstrated that the uptake of phosphate by clover is reduced at low temperatures.

Other work relevant to temperate Australia has been conducted in New Zealand. Scott and Jowett (1980) at Invermay have also reported on the effects of time of application on seasonal responses to superphosphate. At Te Kuiti, Roach *et al.* (1996) measured growth using a 'trim/cut technique' to assess the growth of pasture within an exclosure and found that the percentage response to fertiliser was similar in all seasons, but the magnitude of the response was greater in seasons where pasture production was greater (spring and summer). Response to fertiliser is sometimes expressed in terms of relative yield by scaling yield in terms of the treatments receiving non-limiting or maximum doses of fertiliser (Smith and Gregg 1982; Risk and Smith 1992).

In most cases, only 2 or 3 rates of fertiliser have been compared. This is insufficient to describe the response in terms of functions which can be used for modelling production systems (Helyar and Godden 1977).

In the course of a project to compare the response of pastures to superphosphate under conditions of mowing or grazing (Cayley and Hannah 1995), the pasture production of grazed pastures during winter, spring, and summer for 4 years was assessed by measuring pasture accumulation within pasture cages which were moved monthly. The measurements were continued for a further 3 years after fertiliser use ceased. Our objective was to use these results to examine the effects of the phosphorus status of the pastures on seasonal pasture growth. The recent emergence of the decision support system (DSS), GrassGro (Freer *et al.* 1997; Moore *et al.* 1997), has enabled implications for animal production to be examined over a range of conditions.

Materials and methods

Experimental site

The study was conducted at the Pastoral and Veterinary Institute, Hamilton (37° 49′ S, 142° 04′ E; altitude 200 m), between 1979 and 1987. The Institute is situated on duplex soils derived from basalt, which are typical of much of south-western Victoria. The mean annual rainfall (1962–1996) is 703 mm with a winter incidence. The experiment was established on pasture that was sown in 1977. At sowing, 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 was sown with an oat crop with 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 pasture species 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. Further details of the site have been provided by Cayley and Hannah (1995). Monthly rainfall for each year of the study and the time during which measurements were made are shown in Fig. 1.

Design

A non-replicated factorial design was used. Six levels of superphosphate in factorial combination with 3 stocking rates were allocated in random sequence to 18 plots. Differences in stocking rate were brought about by varying the area of the plots, the number of sheep per plot being constant.

Management

In the course of investigations reported here, the site was managed in 2 phases: the 'build-up' phase when superphosphate

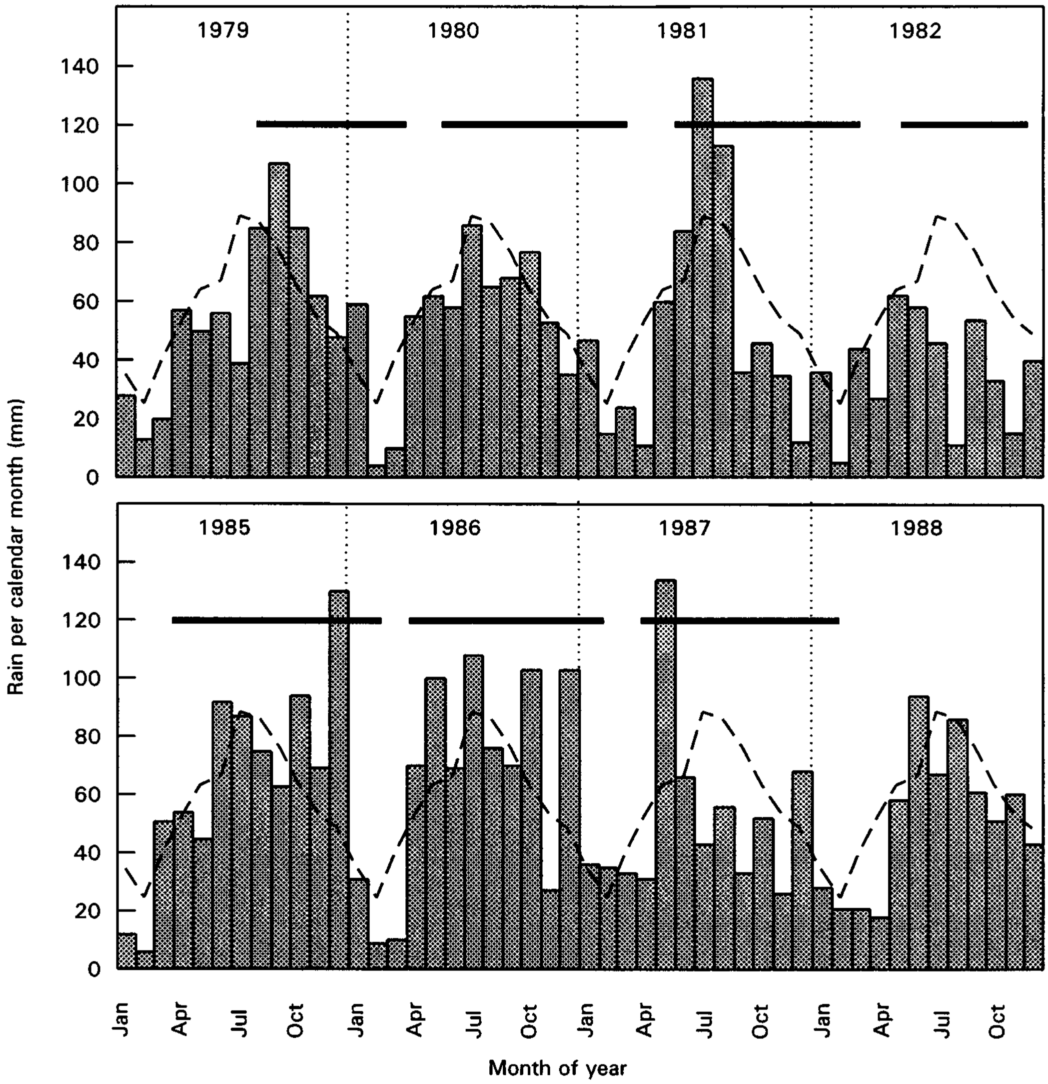

Fig. 1. Rainfall during the experiment. The dashed line represents mean annual rainfall from 1962 to 1996. Wide horizontal lines signify periods over which measurements were made.

was applied to the plots, and the 'run-down' phase during which plots received no fertiliser.

During the build-up phase (1979–1984), the fertiliser was evenly applied to the soil surface in mid July in 1979, early May in 1980 and 1981, and late April in 1982 and 1984 by using a modified seed drill. The rates of single superphosphate, expressed as total phosphorus (P) applied per hectare (Table 1), were calculated by fixing the lower rate and upper rate, then using a progression based on equal increases of the square root of rate of P to calculate the intermediate rates. The upper rate of P was 100 kg/ha in 1979 and 1980, 60 kg/ha in 1981, and 40 kg/ha in 1982 and 1984. The lower rate was 4 kg/ha in 1984 and zero for the other years. Potassium chloride was applied to all plots in the first 3 years of the experiment, 100 kg/ha in 1979, 94 kg/ha in 1980, and 56 kg/ha in 1981. From 1979 to 1982, the plots were stocked with individual groups of wethers and pastures were measured monthly (Figs 1 and 2).

The plots were de-stocked on 29 November 1982 due to drought, and remained ungrazed until early June 1983. On 16 February 1983, the plots were partly burned by a grassfire, but the pasture did not sustain serious damage, as regeneration following rain during the 1983 autumn appeared to be normal. The lack of damage to perennial grass plants and seed of annual species was probably due to the low herbage mass

Table 1. Rates of P (kg/ha·year) applied as single superphosphate to pastures at the six levels from lowest to highest

Year	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
1979	0·0	4·0	16·0	36·0	64·0	100·0
1980	0·0	4·0	16·0	36·0	64·0	100·0
1981	0·0	2·4	9·6	21·6	38·4	60·0
1982	0·0	1·6	6·4	14·4	25·6	40·0
1983	0·0	0·0	0·0	0·0	0·0	0·0
1984	4·0	8·2	13·9	21·1	29·8	40·0
1985–1987	0·0	0·0	0·0	0·0	0·0	0·0
Total	4·0	20·2	61·9	129·1	221·8	340·0

present at the time of the fire. However, most of the fencing was destroyed. The wire netting of the remaining fences was removed and the area was grazed in common with sheep. The plots were re-fenced during the spring, but gateways were left open allowing stock free access to all plots. No fertiliser was applied in 1983. All plots were fertilised in April 1984, and were grazed until March 1985 by rotating 3 flocks of approximately 50 wethers through the plots to ensure that they were all evenly grazed. No measurements of pastures or animals were made during this period.

During the run-down phase (1985–1987), the site was used for another experiment (Cayley *et al.* 1987), in which the response to superphosphate applied to strips in 2 fenced exclosures (each 8 m by 7·5 m) within each plot was measured. No fertiliser was applied to the remaining grazed portion of the plots, which were again grazed by individual groups of young wethers. Pastures were measured monthly as before.

Animals

One-year-old Corriedale wethers were used as experimental animals. New sheep were used each year, and details of their management during the build-up phase are given by Cayley and Hannah (1995). In brief, 8 animals were used per plot in all years except 1981. The low, medium, or high stocking rates during these years were 10, 14, or 18 sheep/ha, respectively. Seven animals were used per plot during 1981.

Similar sheep were used during the run-down phase. In 1985 and 1986, each plot was stocked with 8 wethers. As the study progressed it became increasingly apparent that stocking the plots at the lowest levels of fertiliser resulted in excessive stress on the animals, particularly at the high or medium stocking rates, due presumably to the diminishing effectiveness of previously applied fertiliser. At the same time it was also apparent that pastures fertilised at the highest rates were not being well utilised at the highest stocking rate. The stocking policy was changed in 1987 in order to address these concerns. This was done by varying the numbers of sheep per plot according to the level of fertiliser (Table 2).

Table 2. Stocking rate (sheep/ha) of treatments during the final year of the run-down phase (1987)

Grazing pressure	Level of fertiliser 1	2	3	4	5	6
Low	7·5	8·75	10·0	10·0	11·25	12·25
Medium	10·5	12·25	14·0	14·0	15·75	17·5
High	13·5	15·75	18·0	18·0	20·05	22·5
Sheep/plot	6	7	8	8	9	10

Measurement of pastures

The growth of the pastures and the proportion of green pasture present were assessed monthly. References here and in the literature to measurements of 'pasture production' or 'pasture growth' often should be described as pasture or herbage accumulation or net accumulation (see Hodgson 1979 and **Discussion** below). The procedure for measuring pasture accumulation was based on taking measurements with a weighted disk pasture meter (Bransby *et al.* 1977) at marked sites. The sheep were prevented from grazing these sites during the following month by placing a cage of welded mesh over each marked site. The marked positions were re-measured after the month was completed. Six sites for cages, each positioned on the median of a set of 5 measurements made at random, were used per plot. The procedure is described in detail elsewhere (Cayley and Hannah 1995; Cayley and Bird 1996).

The proportion of green pasture present in each plot was assessed by hand-sorting duplicate subsamples taken from a sample obtained from approximately 30 'toe cuts' per plot (Cayley and Bird 1996). The 'toe cuts' were collected by walking a zigzag course down each plot and cutting the pasture from an area of approximately 30 cm^2 immediately in front of the toe every 15 steps. The pasture was cut as close as possible to ground level as the constraint of avoiding contamination with soil would allow. The bulked 'toe cut' sample from each plot was dried at 60°C to constant weight. The subsamples were taken by a quartering procedure (Cayley and Bird 1996) and sorted into green and dead herbage, and the proportion of green herbage was computed. If the difference between subsamples exceeded 5 percentage units, a third subsample was taken and the mean proportion of green computed. This was rarely required: 45 out of 1296 cases in 7 years, including 23 cases in the first 54 determinations.

Imputation of seasonal pasture production

The pattern of pasture dry matter (DM) production within and between years was assessed by examining graphs of the progressive increase of pasture during each year of the study (Fig. 2). These graphs represent a progressive monthly total of net accumulation, averaged over the 3 stocking rates, at each level of P.

Three phases of growth were apparent in each year. These comprised a period where the rate of accumulation of pasture was linear (phase A), a period when accumulation was occurring at a greater or steadily increasing rate (phase B), and a phase when accumulation was at a low level (phase C). For the sake of simplicity, phase A is referred to as 'winter', phase B as 'spring', and phase C as 'summer'; despite the fact that the phases of growth did not correspond precisely with the conventional definition of seasons of the year (Radcliffe 1974), the 3 phases of growth are hereafter referred to as 'seasons'. The pattern of accumulating pasture was similar for different stocking rates within each year, but there was considerable variation between years. This reflected seasonal differences and differences due to the time of commencing measurements.

With the exception of 1982, the pattern of accumulating pasture was also consistent between levels of P, in that the starting date of each phase of growth was the same for each level of P. In 1982, a drought year, the end of phase B was determined from the pattern of accumulating pasture in P levels 3–6 to be on Day 283 from the start of 1982 (Fig. 2). At the 2 lowest levels of P, the pasture continued to grow at the same rate up to the middle of phase C. Production from these plots during this time was included in phase C.

The pasture accumulation for a season usually comprised measurements during a number of periods, which varied in duration. The growth of each plot during any season G_s (in t DM/ha·season) was calculated as follows:

$$G_s = \frac{\sum_{i=1}^{n} R_i T_i}{1000} \tag{1}$$

where n is the number of periods in a season, R_i is growth rate over any period i (kg DM/ha·day), and T_i is duration (in days) of any period i.

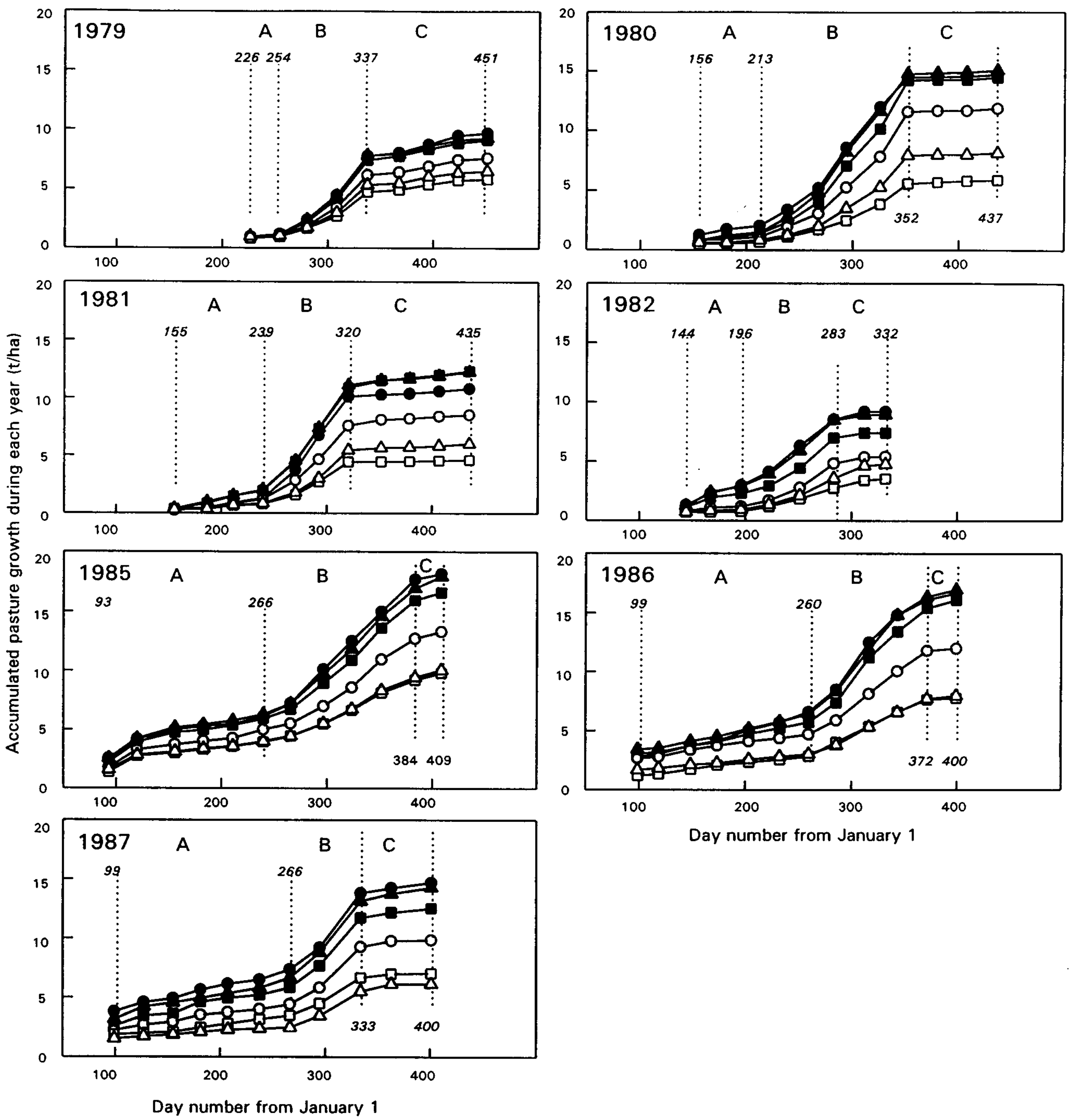

Fig. 2. Cumulative production of pasture (t DM/ha) for each year. Periods marked A, B, and C correspond to different phases of pasture growth, designated as 'winter', 'spring', and 'summer', respectively. The day number from the start of each year corresponding to the beginning and end of each phase is also given. P level: 1 □, 2 △, 3 ○, 4 ■, 5 ▲, 6 ●.

The pasture accumulation during winter was calculated by adding the amount of green pasture present at the beginning of phase A each year to the remaining pasture that grew during phase A. This was because there had always been some growth before the estimation of pasture production using cages commenced each year, and the amount of green pasture at the start of measurements was our only estimate of pasture growth up to this point. Phase A varied from 1 month in 1979, due to the experiment starting in late winter, to approximately 6 months in 1986 and 1987.

Table 3. Analysis of variance of pasture accumulation: (I) to detect stocking rate (SR)×P status interactions, and (II) to assess contribution due to fertiliser level (FL), stocking rate, year, and season

For (I), 3 levels of P status comprise fertiliser levels 1 and 2, 3 and 4, and 5 and 6, respectively. Data from 1986 were excluded

Source of variation	(I) SR·P status term embedded in ANOVA			(II) Residual terms here include SR·P status		
	d.f.	Mean square	*P* value for *F* ratio	d.f.	Mean square	*P* value for *F* ratio
			Plot stratum			
SR	2	4·35	0·086	2	4·35	0·023
FL	5	51·52	<0·001	5	51·52	<0·001
SR·P status	4	0·21	0·941			
Residual	6	1·149		10	0·774	
			Plot·year stratum			
Year	5	46·74	<0·001	5	46·74	<0·001
Year·SR	10	0·74	0·029	10	0·74	0·003
Year·FL	25	1·11	<0·001	25	1·11	<0·001
Year·SR·P status	20	0·13	0·977			
Residual	30	0·304		50	0·233	
			Plot·year·season stratum			
Season	2	1006·39	<0·001	2	1006·39	<0·001
Season·SR	4	0·37	0·185	4	0·37	0·184
Season·FL	10	19·53	<0·001	10	19·53	<0·001
Season·year	10	49·14	<0·001	10	49·14	<0·001
Season·SR·year	20	0·31	0·175	20	0·31	0·177
Season·FL·year	50	1·20	<0·001	50	1·20	<0·001
Season·SR·P status	8	0·24	0·433			
Residual	112	0·234		120	0·234	
Total	323			323		

Modelling using the GrassGro DSS

Animal production from January 1970 to December 1995 at Hamilton was modelled using GrassGro for Windows 2.0.1. (Moore *et al*. 1997). Daily climatic data collected at the Pastoral and Veterinary Institute weather station were used. The pasture was a mixture of perennial ryegrass (cv. Victorian) and subterranean clover (cv. Leura). Medium Merino ewes were mated on 18 December or 5 April to medium Merino rams. This resulted in mean lambing dates of 15 May or 1 September, respectively. For each time of lambing, simulations were conducted using 3 soil fertility levels and up to 7 stocking rates. Current costs and prices were used to allow gross margins to be calculated for each simulation run. These, together with remaining physical and managerial details used in the simulations, are provided in Appendix 1.

Statistical analysis

First we used the analysis of variance (ANOVA) to make an assessment of the influence of all factors that contributed to variation in pasture accumulation. For the purpose of this analysis the experiment was regarded as a split-split-plot design: that is plots split for year split for season. The variance was thus partitioned into 3 strata (Table 3). Because the experiment was unreplicated, pure error residual terms were unavailable; these were estimated from the highest order interaction terms available in each stratum.

Doubt would be cast on this approach if there was a statistically significant stocking rate×P level interaction. The data were therefore examined for an interaction between stocking rate and P status by combining P levels 1 and 2 to give 6 plots with a low P status, combining P levels 3 and 4 to give 6 plots with a medium P status, leaving the remaining 6 plots with a high P status. The stocking rate×P status interaction was embedded in the ANOVA (Table 3 part I). Residuals were checked graphically for heterogeneity of variance against fitted values and also by year and season of growth. Residuals for 1986 were more variable than those of the other years, so these data were excluded from the overall ANOVAs presented in Table 3. The 1986 data were analysed separately in order to assess the effects of stocking rate (Table 4) and P level (Table 5). There were no significant interactions between stocking rate (or grazing pressure in the case of 1987 data) and P status in any stratum (Table 3 part I). This gave us confidence to include these terms in the highest order interaction for each stratum which was then used as the residual sum of squares for assessing the effects of the various main effects and interactions (Table 3 part II).

The standard error of the difference (s.e.d.) in pasture accumulation between P levels in each of the 21 seasons studied and also total pasture accumulation (Table 5) were computed by means of a separate ANOVA for each occasion using the P level×stocking rate terms for error in the same manner as the plot stratum residual variance (Table 3 part II), that is with 10 degrees of freedom for the residuals.

Comparisons of differences in shape of the curves depicting cumulative seasonal pasture accumulation in terms of P fertiliser applied were restricted to winter and spring because levels of production during summer were low and response to fertiliser quite variable (Table 5). It was necessary to fit a different set of response curves each year, as the fertiliser rates varied each year, and growth of pasture would have been influenced by the varying residual value of previous fertiliser applications.

We used the hyperbolic function (Eqn 2) to describe cumulative seasonal yield y, averaged over stocking rates, in terms of P fertiliser rate x. Here A, B, and C are constants.

$$y = A - B/(1 + Cx) \qquad (2)$$

Table 4. Effect of stocking rate (averaged over all levels of fertiliser) on annual herbage accumulation (t DM/ha)
Data from 1986 were analysed separately. For comparing means within all years except 1986: l.s.d. ($P = 0\cdot05$) = 1·142 t DM/ha. For comparing means averaged over all years except 1986: l.s.d. ($P = 0\cdot05$) = 0·800 t DM/ha. For comparing means for 1986: l.s.d. ($P = 0\cdot05$) = 1·286 t DM/ha

Stocking rate	1979	1980	1981	1982	1985	1986	1987	All years[A]
Low	9·20	11·88	8·76	6·97	14·36	(11·19)	9·16	10·05
Medium	8·16	11·95	9·13	6·65	15·31	(10·95)	9·39	10·10
High	6·57	11·21	9·33	5·98	13·14	(9·63)	7·97	9·03

[A]Average for all years except 1986.

Because no fertiliser was applied during 1985–1987 (Table 1), we used total P applied from 1979 to 1984 for the variate 'x' during this time. The function was embedded in the ANOVA using nonlinear contrasts (Butler and Brain 1993) of the fertiliser rate and fertiliser rate×season of growth means. The nonlinear contrasts were fitted to the P fertiliser rate means by partitioning the sum of squares for P rate into the sum of squares for the 'curve' and the remainder for the 'deviations'. Similarly, the P rate×season interaction sum of squares was partitioned into 'common nonlinear' for the winter or spring phases of growth, the sum of squares due to having 'separate curves', and the remaining sum of squares for the 'deviations'. Estimates of A, B, and C and their variance–covariance matrix were obtained by generalised nonlinear least squares (Seber and Wild 1989) on the fertiliser rate×season of growth means, using the variance–covariance matrix for these means obtained by Residual Maximum Likelihood under the same model as was specified in the ANOVA. Where the ANOVA indicated significant nonlinear contrasts between season of growth, s.e.d.s for the coefficients A and B were computed for pairwise comparisons. Residuals were checked graphically for heterogeneity of variance against fitted values and by season of growth.

All statistical analyses were performed using the GENSTAT 5·3 software (Genstat 5 Committee 1993).

Results

Effect of stocking rate

When averaged over fertiliser rates and years, pasture production was greater at low and medium stocking rates than at the high stocking rate. There was inconsistency in this trend between years as indicated by a significant interaction (Table 3 part II) between stocking rate and year ($P < 0\cdot01$). Pasture accumulation was depressed at the high stocking rate in 4 of the years, but in others no trend was apparent (Table 4). There was no significant season×stocking rate interaction.

Effect of fertiliser

Differences in response to fertiliser between seasons and years (Table 5) show that the pasture responded to P fertiliser in every winter except 1979. Spring growth was strongly related to fertiliser in all years, but growth during summer did not show a consistent pattern of response. Pasture production appeared stable at the higher levels of fertiliser, suggesting that these levels were sufficient to provide an estimate of asymptotic yield.

The response to fertiliser varied with season and year, so that the fertiliser level×season, fertiliser level×year, and fertiliser level×season×year interactions (Table 3 part II) were all highly significant ($P < 0\cdot001$). The effect of fertiliser level on the production of pasture during each season (averaged over stocking rates and years) may be calculated from results (excluding those from 1986) presented in Table 5. The overall difference in pasture production between the highest and lowest producing fertiliser levels for each season was greatest for spring and least for summer. These differences were 1·48, 4·85, and 0·31 t DM/ha for winter, spring, and summer, respectively. The l.s.d. ($P = 0\cdot05$) for all comparisons within seasons was 0·425 t DM/ha.

Response curves

Pasture accumulation during winter and spring (Table 5) was used to fit response curves to fertiliser rate. Values for the independent variable (fertiliser applied each year during 1979–1982, or total fertiliser applied during the build-up phase for 1985–1987) are given in Table 1. We used the ANOVA (Table 6) to determine if it was appropriate to use a separate A coefficient for winter or spring (significant F ratio for 'season') or separate B coefficients for each season (significant F ratios for 'common nonlinear'), or a separate C coefficient for each season (significant F ratio for 'separate curves'). The term 'curve' was always significant, but 'separate curves' was not. This meant that coefficient C, the rate at which asymptotic yield is approached, did not differ significantly between winter and spring in any of the 7 years. Asymptotic yield is given by coefficient A, and differed between seasons each year ($P < 0\cdot001$). Coefficient B, the difference between the yield with no fertiliser and asymptotic yield, differed between winter and spring for all years except 1987 ($P < 0\cdot01$); however, we also fitted a separate B coefficient for each season of that year (see **Discussion** below).

Effects due to stocking rate were only detected in 2 years, and an interaction between stocking rate and season in the first year only ($P < 0\cdot05$). The interaction was due to a greater influence of stocking rate on production in spring compared with winter

Table 5. Effect of level of fertiliser (1–6, see Table 1), averaged over three stocking rates, on seasonal and yearly herbage accumulation (t DM/ha), over seven years

Year	Fertiliser level 1	2	3	4	5	6	l.s.d. ($P = 0{\cdot}05$)	Sign. of F-ratio
				Winter				
1979	0·99	1·10	1·00	1·14	1·07	1·19	0·278	n.s.
1980	0·68	0·87	1·13	1·39	1·49	2·04	0·615	**
1981	0·82	0·88	1·24	1·99	2·04	1·30	0·701	**
1982	0·78	0·95	1·21	2·30	2·91	2·99	0·769	***
1985	3·91	3·96	4·96	5·88	6·25	6·07	1·350	**
1986	1·72	1·48	2·19	2·83	3·19	3·99	0·844	***
1987	2·13	1·44	2·77	3·78	4·29	4·35	1·143	***
				Spring				
1979	3·76	4·23	5·16	6·27	6·72	6·57	0·631	***
1980	4·90	7·08	10·47	12·87	13·30	12·47	2·143	***
1981	3·61	4·57	6·34	8·87	9·03	8·78	0·732	***
1982	1·98	2·63	3·61	4·68	5·54	5·55	0·773	***
1985	5·25	5·42	7·71	10·03	10·67	11·59	1·702	***
1986	4·83	4·70	7·11	9·66	9·92	9·54	2·074	***
1987	3·18	3·03	4·83	5·89	6·48	6·45	1·635	***
				Summer				
1979	1·06	1·15	1·41	1·69	1·45	1·91	0·397	**
1980	0·28	0·19	0·27	0·20	0·28	0·19	0·210	n.s.
1981	0·19	0·57	0·94	1·42	1·17	0·71	0·495	**
1982	0·78	1·17	0·57	0·43	0·47	0·66	0·791	n.s.
1985	0·60	0·63	0·59	0·67	0·99	0·47	0·514	n.s.
1986	0·13	0·25	0·19	0·70	0·58	0·54	0·809	n.s.
1987	0·38	0·62	0·59	0·81	1·14	0·88	0·503	n.s.
				Total				
1979	5·80	6·49	7·57	9·10	9·24	9·66	0·994	***
1980	5·86	8·13	11·87	14·46	15·07	14·70	1·542	***
1981	4·61	6·01	8·51	12·28	12·23	10·79	1·123	***
1982	3·54	4·74	5·39	7·41	8·92	9·19	1·319	***
1985	9·75	10·01	13·25	16·57	17·90	18·14	2·431	***
1986	6·68	6·44	9·48	13·19	13·69	14·06	1·820	***
1987	5·69	5·08	8·18	10·48	11·91	11·68	2·642	***

**$P \le 0{\cdot}01$; ***$P \le 0{\cdot}001$; n.s., not significant ($P > 0{\cdot}05$).

during that year; pasture accumulation per hectare was depressed by 0·15 t DM/sheep in spring and by 0·056 t DM/sheep during winter (s.e.d. for slope = 0·018 t DM/sheep). Despite these effects due to stocking rate, we fitted the same model each year, using the mean growth per season, averaged over the 3 stocking rates.

The significance of the 'deviations' from the specified nonlinear model (Eqn 2) in 1981 indicated that a different model could be specified for this year. A model that gave a slightly better fit (Eqn 3)

$$y = A - Dx - B/(1 + Cx) \qquad (3)$$

had the additional coefficient D. As P levels increase, this response curve approaches an asymptote defined by the equation $A - Dx$. In this case the F ratio for 'deviations' from the specified model was not significant ($P = 0{\cdot}211$). When the 1981 data were fitted to the model specified in Eqn 3, the 'separate curves' component of the P×season term was also not significant, so that our general finding of lack of difference in the coefficient determining curvature of the fitted line remained the same. This, together with the impression that changing one point could make the difference between the 2 models, led us to reject the more complex model. An additional reason for rejection was that in the more complex model the coefficients A, B, and D had less obvious biological counterparts.

The values of the A, B, and C coefficients for winter and spring for each of the 7 years are given in Table 7. The asymptotic value for pasture produced was always greater for spring, and the response to fertiliser was also greater for spring in all years except 1987. Fitted curves are shown in Fig. 3. These curves illustrate the significant interactions detected in the original ANOVA (Table 3).

Table 6. Analysis of variance used to detect the effects of superphosphate application rates and stocking rate on the growth of pasture (y) during winter or spring

Model: $y = A - B/(1 + Cx)$, where x = rate of P, and A, B, and C are constants. Coefficients A, B, and C correspond respectively to 'season', 'common nonlinear', and 'separate curves' in the plot×subplot stratum

Source of variation	d.f.	MS	Sign.	MS	Sign.	MS	Sign.	MS	Sign.
		1979		**1980**		**1981**		**1982**	
Build-up phase: (x = P applied in autumn)									
Plot stratum									
P rate	5	2·59	***	22·59	***	12·33	***	9·31	***
Curve	2	6·35	***	55·79	***	28·52	***	22·92	***
Deviations	3	0·08	n.s.	0·46	n.s.	1·54	***	0·24	n.s.
Stocking rate	2	2·00	***	0·51	n.s.	0·24	n.s.	1·07	*
Residual	10	0·10		0·35		0·20		0·24	
Plot·subplot stratum									
Season	1	171·72	***	715·16	***	271·08	***	41·37	***
P rate·season	5	2·21	***	14·05	***	5·65	***	0·50	*
Common nonlinear	1	10·75	***	66·21	***	27·79	***	2·06	**
Separate curves	1	0·01	n.s.	0·51	n.s.	0·03	n.s.	0·28	n.s.
Deviations	3	0·10	n.s.	1·18	n.s.	0·15	n.s.	0·05	n.s.
Stocking rate·season	2	0·42	**	0·29	n.s.	0·03	n.s.	0·02	n.s.
Residual	10	0·047		0·48		0·105		0·115	
Total	35								
		1985		**1986**		**1987**			
Run-down phase: (x = cumulative P applied from 1979 to 1984)									
Plot stratum									
P rate	5	21·38	***	16·50	***	11·43	***		
Curve	2	52·26	***	39·23	***	22·69	***		
Deviations	3	0·79	n.s.	1·34	n.s.	1·26	n.s.		
Stocking rate	2	2·91	n.s.	1·37	n.s.	1·38	n.s.		
Residual	10	0·98		0·77		0·96			
Plot·subplot stratum									
Season	1	96·48	***	230·40	***	30·79	***		
P rate·season	5	4·34	***	4·02	*	0·30	n.s.		
Common nonlinear	1	21·10	***	15·44	***	1·16	n.s.[A]		
Separate curves	1	0·11	n.s.	1·21	n.s.	0·22	n.s.		
Deviations	3	0·16	n.s.	1·15	n.s.	0·05	n.s.		
Stocking rate·season	2	1·12	n.s.	0·37	n.s.	0·13	n.s.		
Residual	10	0·446		0·745		0·238			
Total	35								

*$P \leq 0{\cdot}05$; **$P \leq 0{\cdot}01$; *** $P \leq 0{\cdot}001$; n.s., not significant ($P > 0{\cdot}05$). [A]($P = 0{\cdot}052$).

GrassGro simulations

The simulation runs predicted that lambs born in spring would be heavier at birth and at weaning than lambs born in autumn. The predicted proportion of lambs weaned per ewe mated was also higher for the spring-lambing system. Fig. 4*a*–*c* shows the relationship between stocking rate, fertility level, and time of lambing on predicted animal sales, wool sales, and supplementary feed costs, respectively. Animal sales increased with stocking rate and soil fertility, and were higher for the spring-lambing system. Wool sales increased with stocking rate and soil fertility, but were not influenced by time of lambing. The requirement for supplementary feed increased with stocking rate and decreased with soil fertility, and was higher for the autumn-lambing system. The combination of these factors led to higher simulated gross margins for the spring-lambing enterprise at all soil fertility levels and all stocking rates.

Fig. 4*d* shows the relationship between the predicted annual gross margin and its standard deviation. The ratio of the standard deviation to gross margin is a measure of risk, and increases as the stocking rate increases. For these simulations, at a given level of gross margin, the standard deviation was greater for the autumn-lambing ewes.

Discussion

Methods of assessing pasture production

Variability in summer growth was considerable. This, and the relatively small proportion of pasture that grew during summer, and its lack of responsive-

Table 7. Values of A, B, and C coefficients of the model $y = A - B/(1+Cx)$ for growth of pasture (y) during winter or spring over seven years

y = t DM/ha·season and x = kg P/ha applied annually from 1979 to 1982, or cumulative P applied from 1979 to 1984 for the remaining years. Units of coefficients A and B, t DM/ha; coefficient C, ha/kg P

Coefficient and season	1979	1980	1981	1982	1985	1986	1987
A (winter)	1·17	1·79	1·99	3·79	7·39	4·20	5·31
A (spring)	7·43	14·21	10·29	6·98	14·29	11·88	7·93
s.e.d.	0·264	0·471	0·320	0·336	1·021	0·871	0·458
t^{A}	23·8	26·4	26·0	9·5	6·8	8·8	5·7
B (winter)	0·16	1·22	1·21	3·20	3·68	3·00	3·88
B (spring)	3·75	9·45	6·83	4·95	9·71	7·84	5·24
s.e.d.	0·281	0·713	0·377	0·438	1·081	1·117	0·633
t	12·8	11·5	14·9	4·0	5·6	4·3	2·2[B]
C (both seasons)	0·0487	0·0982	0·0975	0·0767	0·0080	0·0113	0·0101

[A]Value of t for 10 d.f. (if $t = 2{\cdot}228$, $P = 0{\cdot}05$; if $t = 3{\cdot}169$, $P = 0{\cdot}01$; if $t > 4{\cdot}587$, $P < 0{\cdot}001$).
[B]A separate value of B was fitted for each season in 1987 despite non-significant t-test.

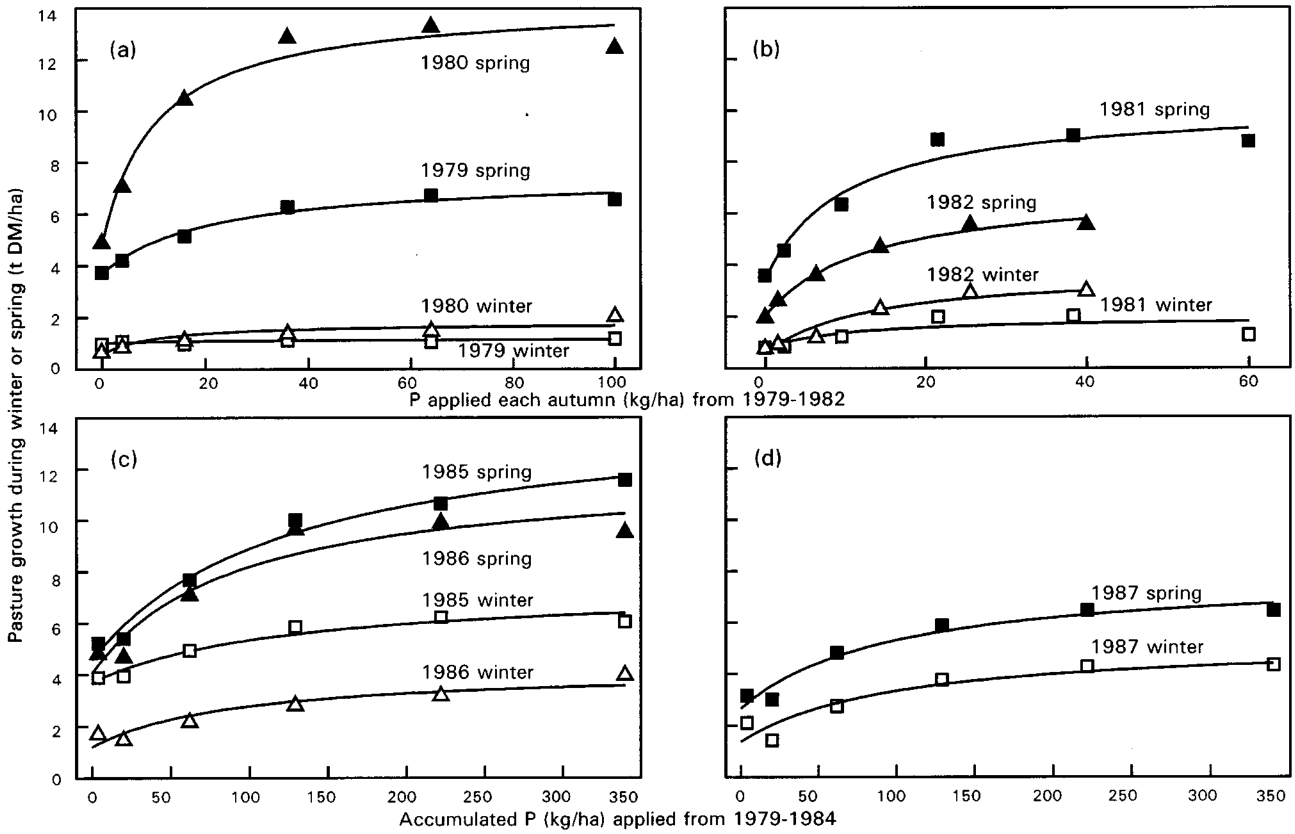

Fig. 3. Response of pasture during winter and spring to P fertiliser applied each year (a) and (b), or to previous applications of P applied from 1979 to 1984 (c) and (d), during which the plots received no fertiliser. Open symbols denote mean values for winter and closed symbols for spring. Curves represent fitted values (see Table 7).

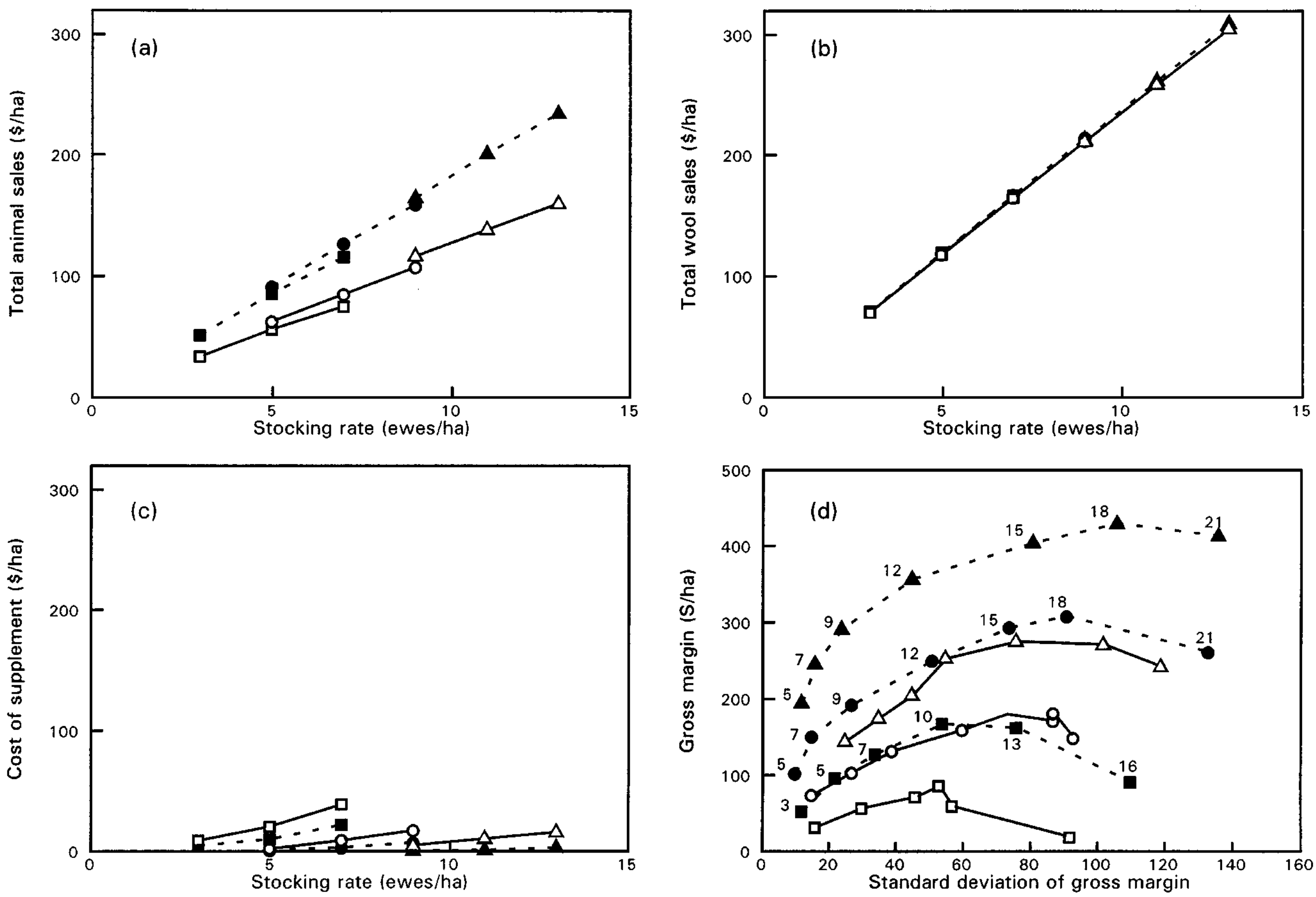

Fig. 4. Output from GrassGro simulations from 1971 to 1995 of fine-wool Merino ewes at a range of stocking rates at Hamilton. Ewes lamb in autumn or spring and production is compared at 3 levels of soil fertility. Graphs depict: (*a*) mean animal sales ($/ha·year); (*b*) mean wool sales ($/ha·year); (*c*) mean supplement costs ($/ha·year); (*d*) the relationship between gross margin and its standard deviation. Numbers in (*d*) near the solid symbols (spring-lambing) denote the stocking rate (ewes/ha). The same stocking rates were used for open symbols (autumn-lambing) of the same shape. P level high ▲, △; P level medium ●, ○; P level low ■, □.

ness to fertiliser, led to us confining our assessments of seasonal responses to the times of the year when pastures were actively growing and assessments of net growth were more reliable.

Studies in Britain have shown that the use of pasture cages can overestimate growth due to rapid growth rates of pastures released from grazing (Parsons *et al.* 1984; King *et al.* 1988). The implications of these findings as they apply to our work have been discussed elsewhere (Cayley and Hannah 1995).

Net pasture accumulation is the difference between true growth and loss of dead herbage by decay. The procedures to estimate true growth (Wiegert and Evans 1964; Lomnicki *et al.* 1968; Cayley *et al.* 1980*a*; Bircham and Hodgson 1983) are very time consuming and were not employed here, so it is not possible to say to what extent net accumulation underestimated the true response to fertiliser. In winter there is a rapid increase in the proportion of green pasture following the opening autumn rains, so that the increase in green pasture should exceed net pasture accumulation at this time. This will also be less than true growth, since true growth is the change in green plus pasture that has senesced but not decayed since the previous measurement. However, an estimate of change in green within the pasture cages may still be a better estimate of response of pasture to fertiliser than estimates of net accumulation.

Reliable estimates of the proportion of green in the cages could not be made at the end of each period. Instead, we assumed that this was the same as the proportion of green of the grazed pasture at that time. After a month there is likely to be a larger proportion of green in the cage than the grazed pasture because animals preferentially select green pasture when pasture is abundant (Hamilton *et al.* 1973; Watson *et al.* 1980). This error probably accounted for every estimate of increase in green in spring being less than corresponding measurements of increase in net herbage. In winter, estimates of increase in green exceeded net pasture accumulation only when the total pasture accumulation was less than about 850 kg DM/ha.

Variation between years

The variation between years and individual seasons in growth of pasture and response to fertiliser (Figs 2 and 3, Tables 3 and 6) can, in part, be attributed to how this study was conducted and how the 'seasons' were defined.

The significant year×P interaction (Table 3) was due mainly to a poor response of pastures to fertiliser in the first year (1979) and the drought year (1982); also to a fall-off in production at the highest level of P in the third year (Table 5, Fig. 2). No explanation for the latter is apparent. Measurements of the botanical composition of the pasture were not made before 1979, but a general impression was that the pasture had a significant proportion of unresponsive species such as *Danthonia* spp., *Romulea rosea* L. (Eckl.), *Anthoxanthum odoratum* L., *Holcus lanatus* L., and *Hypochoeris radicata* L. in 1978. The site received no fertiliser that year. This, coupled with a late application of fertiliser (McGowan and Cameron 1972; Scott and Jowett 1980), probably resulted in the small response to fertiliser in 1979.

The lesser production during winter in the first 3 years of the build-up phase compared with later years cannot necessarily be interpreted as a lack of effectiveness of fertiliser for promoting winter growth in newly upgraded pastures. These measurements were also associated with different times of application of fertiliser (it was applied earlier in 1982) and length of 'winter' (Fig. 2). The maximum response to fertiliser ('*B*' coefficient, Table 7) was greater in spring than winter in all years. This effect just failed to reach statistical significance in 1987 (see significance of variance ratio for 'common nonlinear' in Table 6); however, we considered that fitting a separate '*B*' coefficient for each season in 1987 was biologically appropriate. The absolute response to the fertiliser was greater in spring in all of the years (Table 5).

Variation in production during 'spring' contributed to significant interactions. The high level of production during this season in 1980 and 1985 was associated with years of good spring rainfall so that the growing seasons were extended (Fig. 2). Spring production was poor in 1982 (drought) and 1987 (fourth successive year without fertiliser, coupled with below-average rainfall during spring).

Effects of stocking rate

The decrease in net pasture accumulation associated with increasing stocking rate that we detected on some occasions is consistent with similar findings for sheep (Curll 1977; Lodge and Roberts 1979) and steers (Cayley *et al.* 1980*b*). The work with cattle also compared the effect of stocking rate on true pasture production, and showed that the depression of true growth increased with increasing stocking, a state of affairs that is likely to apply to the pastures grazed with sheep. Other work, for example Birrell *et al.* (1974), has shown that pasture production, while being reduced at high stocking rates, may also be less if the stocking rate is very low. Bircham and Crouchley (1976) compared the growth of pasture stocked by ewes at 15 ewes/ha or 22 ewes/ha and found that pasture production was less at the higher stocking rate in 2 years out of 5, that it did not differ between stocking rates in 2 years, and that it was greater at the high stocking rate in the final year (this coincided with a change in methodology for assessing growth). We found that net pasture production was depressed on plots at the highest stocking rate during the first year of the build-up phase, and in the run-down phase. When the data were restricted to the build-up phase or the run-down phase, and analysed by ANOVA in a similar manner to that shown in Table 3 part I, we could detect no P status×stocking rate interactions, indicating that the depressing effect of the high stocking rate was not associated with plots where the P status was low. The higher stocking rates used at high levels of P in 1987 may have contributed to the depressing effect of stocking rate on pasture production during that year.

Effects of drought on growth in late spring

In the drought year of 1982, pasture at the 2 lowest levels of P continued to grow in late spring after the growth of the other treatments had slowed (Fig. 2). In the absence of assessments of soil moisture, we can only speculate that this may have been associated with the greater growth of pasture during spring on plots receiving more fertiliser. Martin (1990) has shown a positive relationship between pasture growth and use of soil water. Perhaps the extra growth of pasture on the more heavily fertilised plots was responsible for using up available soil water on these plots first, so that growth here slowed before plots that received little or no fertiliser.

Methods of reporting yields and seasonal responses to fertiliser

A method commonly employed when assessing the responsiveness of pasture is to express the yield in terms of either the most heavily fertilised treatment or an unfertilised 'control' before statistical analysis. Mead (1990) warns against this practice because in this case the divisor is a variable, a fact which complicates the error distribution and '...makes statements of precision much more difficult'. The practice may give a false (optimistic) impression of precision. We have therefore avoided analysing our results in this way. It is, however, possible to express our results in this manner by using the equations described in Table 7.

Other methods of expressing seasonal differences include investigating the effect of P status on the proportion of pasture grown at different times of the year, or the ratio of one season's production to another. These methods are unsatisfactory because of difficulties in interpretation, and because misleading impressions about the effect of fertiliser during a specific season may be gained. For example, the response of pasture to fertiliser in winter was negligible in 1979 (Fig. 3). If the proportion of pasture accumulated in winter is plotted against fertiliser applied, a strong negative trend with increasing P rate is apparent, due to a positive response of pasture to fertiliser in the spring.

Knowledge of likely differences in pasture growth at different times of the year may, however, be used to match the requirement of animal systems to the pattern of pasture production. With the exception of 1987, the difference between spring and winter production, if calculated from the difference between fitted lines (Table 7, Fig. 3), was progressively greater as the amount of fertiliser P was increased. Response curves of the difference between spring and winter growth averaged over stocking rates, on applied P (build-up phase), or accumulated P (run-down phase), were also fitted for individual years by generalised nonlinear regression using the model specified by Eqn 2. This difference approached a value of 90% of the asymptote A at lower rates of applied P in the case of 1982, or accumulated P in the case of 1987, than other years. This may have reflected the lower rainfall in spring of both years, or lessened effectiveness of previous applications of fertiliser in 1987.

The profitability of using fertilisers is determined by how the marginal response to fertiliser (the response in yield per unit of nutrient applied) varies with fertiliser rate. The marginal response in winter or spring during the build-up phase to fertiliser applied each year, or during the run-down phase to total amounts of fertiliser applied, may be determined from the first derivative of Eqn 2 (Cayley and Hannah 1995).

Implications for animal production

Our results showed that for this site, with its history of low fertiliser use, it was possible to double the production of pasture over winter by applying sufficient fertiliser. Willoughby (1959), Bird *et al.* (1989), and Thompson *et al.* (1994) all give relationships between animal production per head and green pasture present. Fitted curves depicting this relationship generally have a slope that decreases with increasing pasture mass, sometimes reaching a point where further increases in pasture mass do not result in corresponding increases in production per head. Increasing pasture production in winter will thus eventually permit the stocking rate to be increased without incurring the penalty of reduced animal production per head.

A consistent finding from our study was that the disparity between pasture grown in winter and pasture grown in spring increased with increasing level of fertiliser. As this disparity widens, the case for a production system that utilises more spring growth before quality deteriorates becomes increasingly compelling.

The presence of excessive dry pasture residue in autumn can adversely affect animal production. Birrell and Bishop (1980) have shown that for pasture systems based on perennial ryegrass and subterranean clover, and grazed by adult wethers at moderate stocking rates (up to 15 sheep/ha), the animals may benefit if a proportion of the area (up to 30%) is used to produce hay in spring which was removed from the system. It is clearly possible to use some of this fodder to supplement deficiencies during poor seasons and droughts to enable the stocking rate to be maintained. However, attempts to transfer feed to augment periods of shortage are unlikely to be completely successful because of the deterioration in quality of the herbage during conservation. Indeed, Birrell and Bishop concluded that feeding hay to sheep on a routine annual basis should be discouraged for this reason.

A simpler approach for utilising well-fertilised pastures is to use animal systems that have their highest demand for feed in spring, and whose requirements are not critical during late summer and early winter when responses to fertiliser are small.

This contention was supported by the GrassGro simulations, which indicated that, for a given level of soil fertility, spring-lambing was more profitable than autumn-lambing, and was less risky at a given level of gross margin. The difference in profitability between these systems was progressively greater as soil fertility increased. Although not tested, it is likely that a sheep system based on wool production from wethers alone would be less responsive to increases in pasture production than a system based on spring-lambing ewes.

Pastures with a high P status may also provide opportunities for diversification of farming enterprises in the higher rainfall areas of southern Australia, as there may be more scope for increasing stocking rate in spring to enable some land to be taken out of pasture and used for some other purpose, spring-grown crops for example.

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Appendix 1. (GrassGro simulations)

Livestock description

Standard reference weight (kg) of non-lactating ewe at condition score* 3	50
Potential greasy fleece weight (kg)	5·0
Maximum fibre diameter (μm)	20
Range in stocking rate (ewes/ha)	3·0–21·0
Mortality (% of flock/year)	2
Initial mean liveweight (kg)	55
Initial mean greasy fleece weight (kg)	1·0

Management

Shearing date: 1 October
Supplementary feeding: maintenance in paddock with wheat when condition score reaches 2
20% of stock cast for age on 31 December at 6–7 years of age
New ewes purchased on 1 January aged 18 months, weighing 50 kg and having condition score 3
Ewes first joined when 1–2 years old
90% conceive singles, 10% conceive twins
Lambs weaned out of the system on 1 September or 20 December
One ram per 50 ewes and rams kept for 5 years

Soil

Steepness:	Level	
Fertility scalar:	0·5, 0·7, or 0·9	
Stage II soil evaporation (mm/day):	4·5	
Physical characteristics:	*Topsoil*	*Subsoil*
Texture	Silty loam	Clay
Cumulative depth (mm)	300	1000
Water content at field capacity (%)	31	42
Water content at wilting point (%)	13	29
Bulk density (g/cm^3)	1·33	1·35
Saturated hydraulic conductivity (mm/h)	6·9	0·8
Initial water content (%)	22	31

Initial state of pasture

Herbage components (kg DM/ha)	*Green*	*Dead*	*Litter*	*Root*	*Seed*	*Phenology state*
Perennial ryegrass	0	1000	200	1500	0	Summer dormant
Subterannean clover	0	0	0	0	400	Senescent

Prices

Wool		
Fibre diameter (μm)	19	21
Fleece (cents/kg clean)	914	723
All wool as % of fleece	90	
Commission, wool tax etc. (%)	8·0	
Sale of lambs		
Value ($/kg dressed weight)	1·0	
Dressing %	45	
Value of skin	0·0	
Sale of cast for age ewes		
Value ($/kg dressed)	1·0	
Dressing %	45	
Value of skin	0.0	

Costs

Shearing		Replacement ewes ($/head)	30·0
Ewes ($/head)	3·50	Rams ($/head)	275·0
Lambs ($/head)	3·00	Commission on sales (%)	5·0
Other husbandry costs		Other sale costs ($/head)	1·20
Ewes ($/head)	3·00	Pasture management ($/ha)	15·0, 22·0 or 30·0
Lambs ($/head)	1·30	Supplement ($/t)	160·0

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