Extending the pasture model in the GRAZPLAN decision support system to evaluate management practices for maintaining improved pastures

FINAL REPORT TO THE MEAT AND LIVESTOCK AUTHORITY

PROJECT CS 230

T.P. Bolger and A.D. Moore

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SUMMARY

Project Objectives

The aims of this project were to (i) improve our understanding of the factors influencing early growth in pastures, and (ii) use this understanding to improve the ability of the GRAZPLAN pasture model (as used in the GrassGro decision support tool) to predict changes in pasture composition. The improved model will be valuable in predicting the impact of pasture management practices on the sustainability and profitability of grazing enterprises in southern Australia.

Graziers frequently experience a loss of legumes and perennial grasses from pastures. These pastures are invaded by less productive annual grasses and broadleaf weeds. In the Sustainable Grazing Systems Key Program, experiments are underway at a number of sites to devise strategies to arrest the decline in pasture composition and productivity. However, determining strategies for the long-term sustainability of grazing systems cannot be achieved quickly or economically by experimentation alone. GrassGro can be used to evaluate the long-term outcomes of pasture management strategies provided that changes in pasture composition can be simulated adequately. In many situations, GrassGro simulates compositional changes realistically. However, there are also some cases where the model fails to predict actual pasture change. This project comprised experimentation and modelling to develop an improved version of the GRAZPLAN pasture model so that it can be used more reliably in developing sustainable and profitable pasture management practices for the grazing industries.

Main Results

The experimental stage of the project addressed processes which govern the establishment of a pasture's composition early in the growing season: germination, growth and partitioning, rooting depth, nutrient responses and competition above and below ground. A range of temperate pasture species (annual and perennial, grass, legume and forb, introduced and native) were studied.

We have quantified the germination responses of ten pasture species to moisture, temperature and depth of placement. The investment of dry matter in shoots and roots during early growth has been measured for 15 species. The rate at which roots penetrate the soil, and the effects of soil texture on this rate, were quantified, as were the distributions of root matter over the rooting depth for up to eight species. These experiments covered the most critical processes in the early stages of seedling establishment. We established that the existing model *structure* appropriately represented the establishment process. The data confirmed the model of temperature responses to germination and allowed us to substantially improve the prediction of rooting depth. The experiments indicated that the model's function describing moisture effects on germination is a simplification but the evidence is not yet strong enough to warrant a change in the model. These experiments enabled us to expand the number of species for which the establishment phase can be modelled.

The results from the experiments on nutrient responses and above- and below-ground competition illustrated the diversity of species responses to soil fertility and the presence of competitors. The interactions were found to be so complex that they could not be used to parameterise or directly test the existing GRAZPLAN pasture model. Instead, they have provided useful insights that have guided our development of a "nutrient-aware" version of the pasture model (working title "NutriAce"), which we intend ultimately to incorporate into GrassGro. The experiment on above- and below-ground competition has clearly demonstrated the *importance* of belowground competition but did not give us sufficient insight into the *mechanisms* of belowground competition for nutrients and water. This will be the subject of further research.

Tests of the modified GRAZPLAN pasture model and parameter set against four field data sets (including three from the Temperate Pasture Sustainability Key Program) were generally successful in simulating available pasture dry matter at all sites. At one TPSKP site (Rutherglen), 78% of pasture composition estimates were within the confidence limits of the data. For two trials at Hamilton, we

were unable to acquire the data necessary to calculate confidence limits for pasture composition. The model predicted the perennial grass component at Hamilton. Although annual grass, clover and broadleaf weeds showed discrepancies at times, these components generally represented low proportions of the pasture biomass. Typically, low pasture proportions will have large relative errors of measurement and the model may not be seriously in error.

A phosphorus x stocking rate experiment at Canberra was also simulated, using the newly developed "nutrient-aware" version of the model. Many of the qualitative responses of the pasture composition in the field experiment were adequately simulated (more clover at high fertility, no substantial effect of stocking rate on clover content, and high clover contents in 1995) but quantitatively the clover proportion predicted by the model often differed from the field values. We think that the "nutrient-aware" model does not adequately simulate soil nutrient availabilities or nutrient uptake rates at this stage.

This project has significantly advanced the development of the GRAZPLAN pasture model. We can now model the emergence process for ten species, six of which had not previously been described. Effects of soil texture on species' rooting depths will be much better estimated. For the three TPSKP experiments, the simulations of composition were plausible; at Rutherglen, 78% accuracy was achieved. In the fourth simulation, where variation in soil fertility was the major factor, composition was not predicted adequately. The nutrient and competition experiments in this project have helped to focus our research to resolve the issues this simulation raises.

1. EXPERIMENTS

1.1. Experiment 1: Integrated seedling establishment and persistence

Competition from established vegetation is a major factor limiting the successful recruitment of seedlings into pasture swards. Some species are better able to colonise gaps than others. The mechanisms that facilitate successful recruitment and the relative importance of competition aboveground (for light) and belowground (for nutrients or water) are poorly understood. Such understanding is needed for the development of an extended version of the GRAZPLAN model which simulates changes in pasture species composition over time.

Eight species were studied to determine the emergence and growth responses of seedlings recruiting into four gap treatments and a non-gap treatment in phalaris swards maintained at a high or low height. The recruiting species included four annual grasses (barley grass, soft brome, annual ryegrass and vulpia), one perennial grass (*Danthonia richardsonii*) two legumes (cluster clover and subterranean clover), and one non-leguminous herb (capeweed). These treatments allowed us to assess recruitment of various pasture species into established swards of Phalaris with competition aboveground, belowground or both in a glasshouse experiment. The two sward-height treatments were maintained by keeping swards clipped frequently to a 5 or 15 cm height. Within each sward height and recruitment species combination, there were five gap-recruitment treatments:

- non-gap, no disturbance or resource (NG) — full root; shoot competition
- gap, no disturbance or resource (UD) — full root; shoot competition
- gap, disturbance but no resource (GC) — partial root; shoot competition
- gap, disturbance and resource (GR) — partial root; shoot competition
- gap, root exclusion tube and resource (RE) — no root; shoot competition

The gaps were circular, 75 mm diameter. In gap treatment 3, a soil core was removed and replaced, causing some soil disturbance and severing all phalaris roots. In gap treatment 4, a soil core was removed and replaced with new soil (resource provision). Gap treatment 5 is similar to treatment 4, but a PVC tube was used to isolate the roots. A total of 48 swards grown in large plastic bins (597 x 362 x 266 mm; 77 litres) represented the sward height x gap species x replicate combinations. The 5 gap treatments were contained within each sward.

There were two phases to the experiment. In the first phase, 50 seeds of the appropriate species were sown into each gap or non-gap treatment. Emergence was recorded weekly through time and as the seedlings grew they were thinned gradually to one per gap treatment. Total percent emergence was calculated. In the second phase of the experiment the recruiting seedlings were allowed to grow for 7 weeks. At that time they were harvested and their dry weight determined as an integrated measure of shoot and/or root competition. Plant tissue as well as soil samples will be analysed for major nutrients in an attempt to determine which nutrients were being contested between the phalaris sward and the recruiting seedlings.

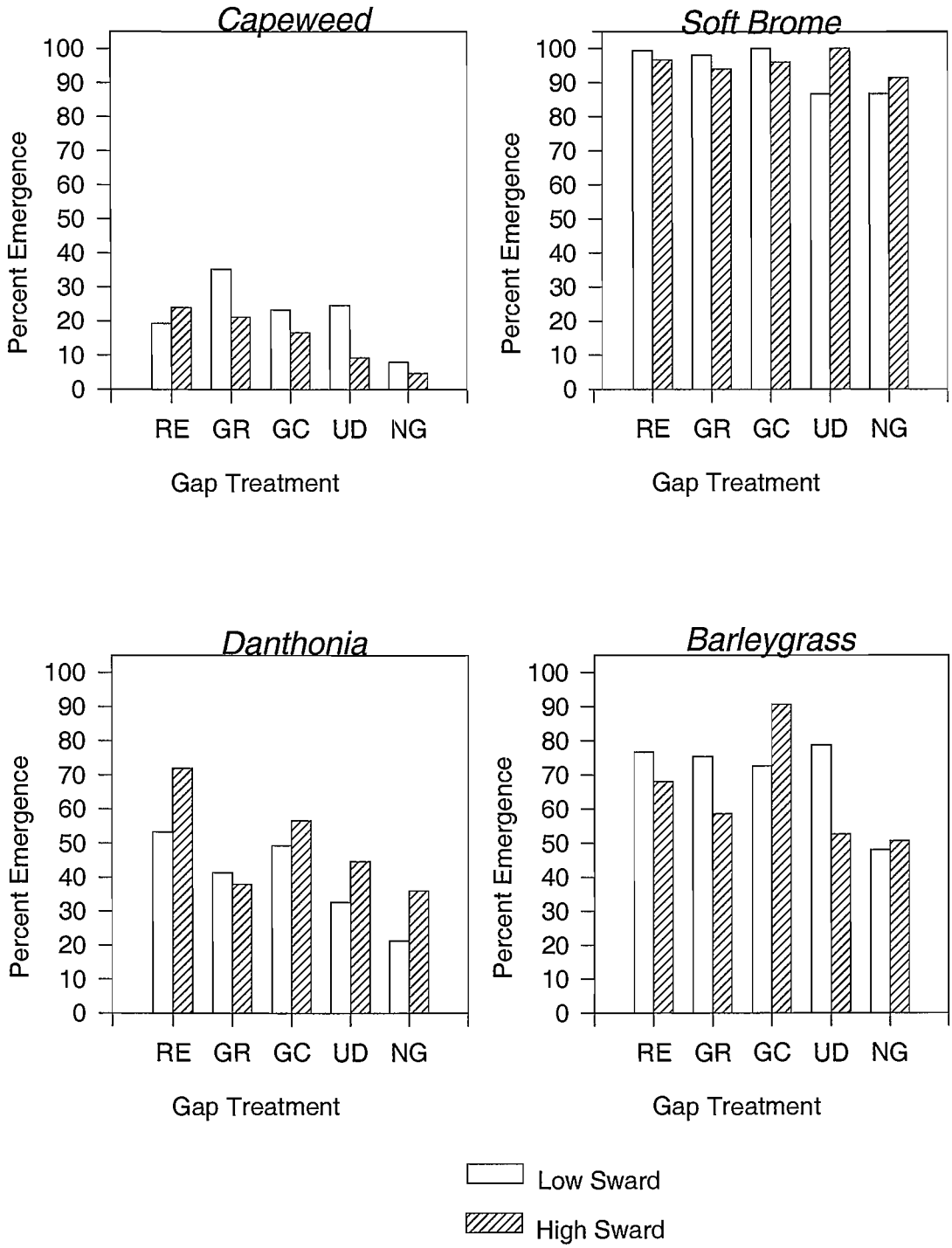
The results of seedling emergence (Figure 1.1) generally showed no effect of sward height on emergence, except for annual ryegrass which emerged better in low swards, and vulpia which emerged better in high swards. There was a non-significant ($P>0.10$) trend for better germination of subclover in high swards. For all species except soft brome the non-gap treatment had significantly lower emergence than the four gap treatments. There were no discernible trends in emergence among the four gap treatments. The mechanisms for these sward and gap effects on germination are not certain, but could be related to vegetation effects on the red:far-red light quality reaching the seeds. It may also be due to other factors such as temperature or carbon dioxide levels related to the presence of vegetation.

In the second phase competition was assessed from the growth (dry weight) of the recruiting plants (Figure 1.2). Growth was better in the low swards for all species except subclover. Subterranean clover did better in high swards in gap treatments (RE, GR) where enhanced soil nutrients (resource) were provided, but better in low swards in gap treatments (GC, UD) without resource provision. In five of the

species (*Danthonia*, annual ryegrass, cluster clover, subterranean clover and vulpia) the best growth was obtained in the gap treatments with resource provision (RE and/or GR). However, for three species (barley grass, soft brome and capeweed) the best growth was obtained outside the root exclusion tube treatment (RE), intended to eliminate root competition. In these cases the best growth was generally in the GR treatment. These results may be explained as assessing the ability of the recruiting seedlings to compete with the phalaris sward for nutrients. Where phalaris is the more competitive species, the recruiting plants did best in the RE and GR treatments. Conversely, species more competitive for nutrients than phalaris did best outside of the RE gap treatment. The UD or GC gap treatments (without resource provision) in the high swards were generally the lowest yielding of the gap treatments. In the low swards, the non-gap (NG) treatment was always the lowest yielding treatment. However, from these results it can already be seen that there are many interactions between the two sources of competition, and their relative effects on recruitment and growth varies among species.

This experiment demonstrates the importance of belowground competition. Further experimental research will be required to determine the mechanisms of belowground competition for nutrients and water in order to incorporate these effects into models.

Figure 1.1. Seedling emergence percentage of pasture species in gaps in low (open bars) or high (shaded bars) swards of phalaris with no (RE), partial (GR and GC) and full (UD) root competition, and in non-gap (NG) areas with full root competition.



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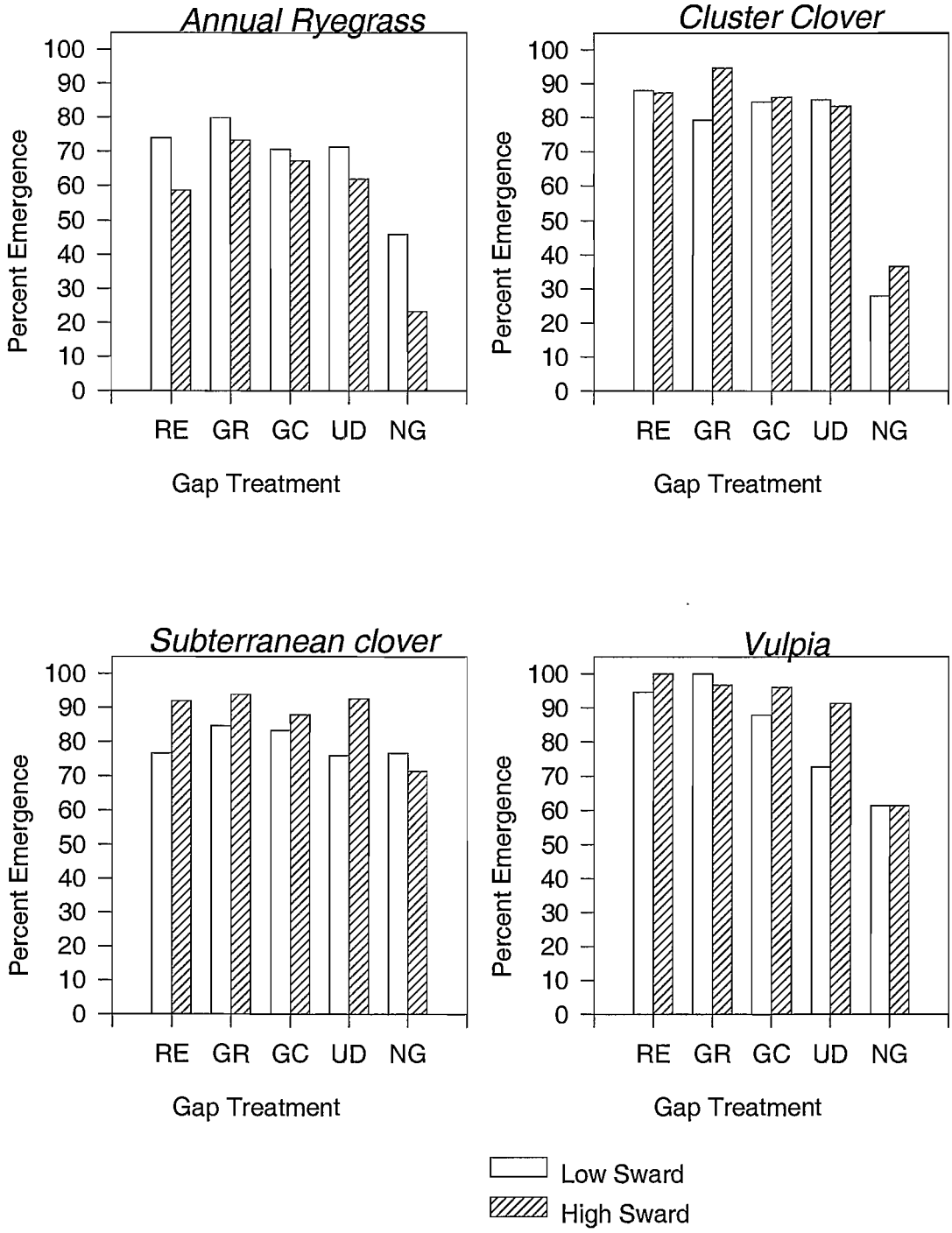
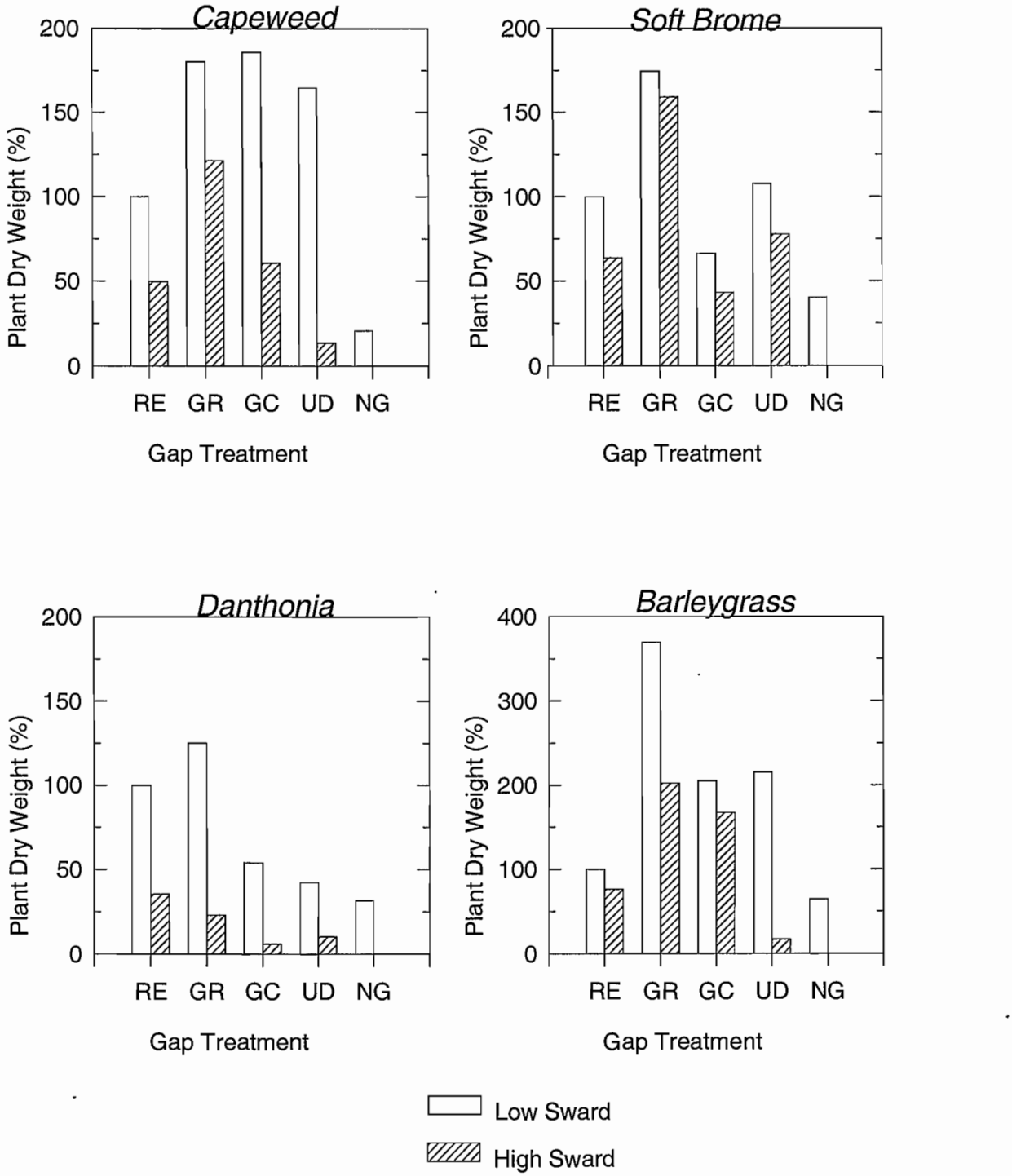


Figure 1.2. Relative shoot growth of pasture species in gaps in low (open bars) or high (shaded bars) swards of phalaris with no (RE), partial (GR and GC) and full (UD) root competition, and in non-gap (NG) areas with full root competition.



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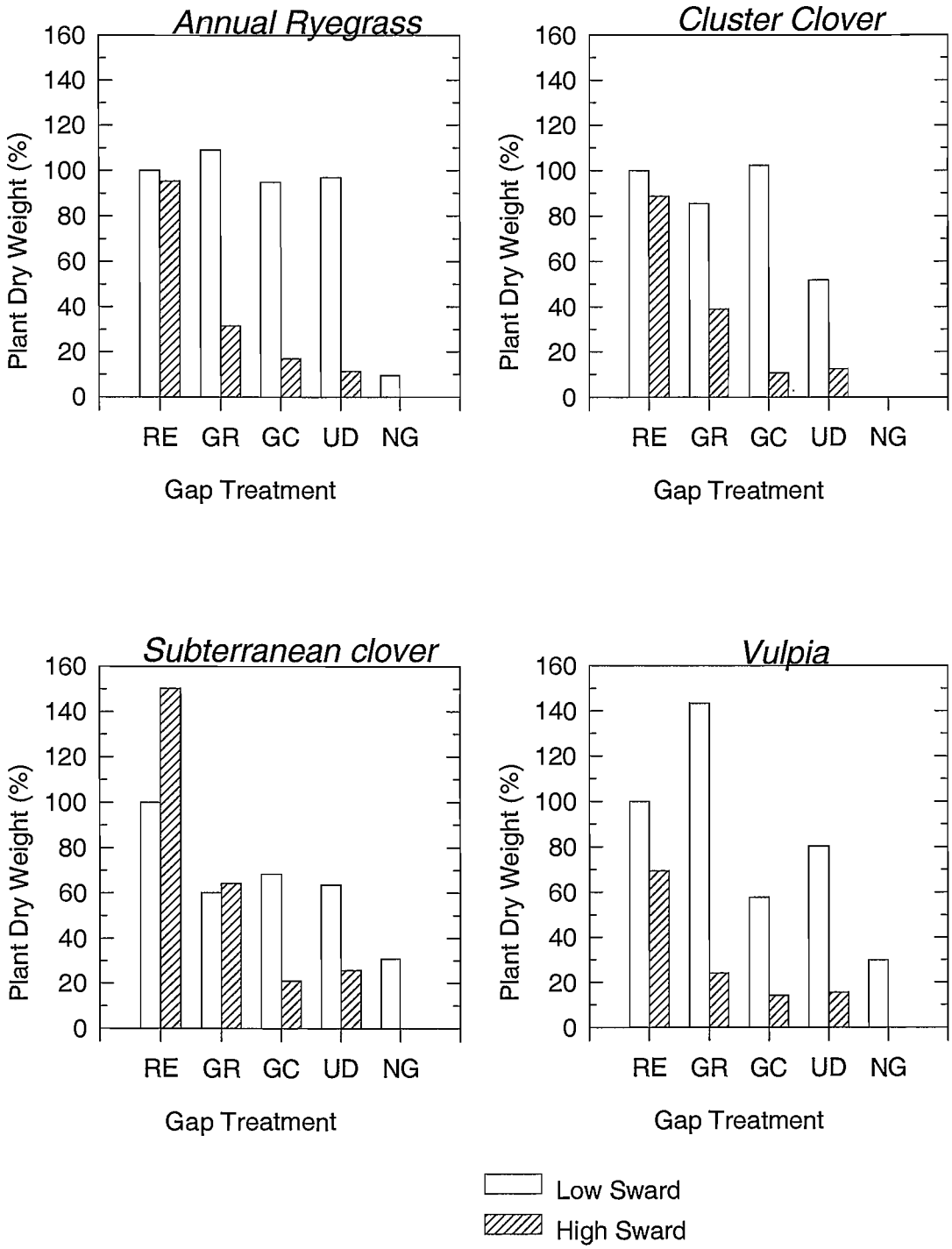
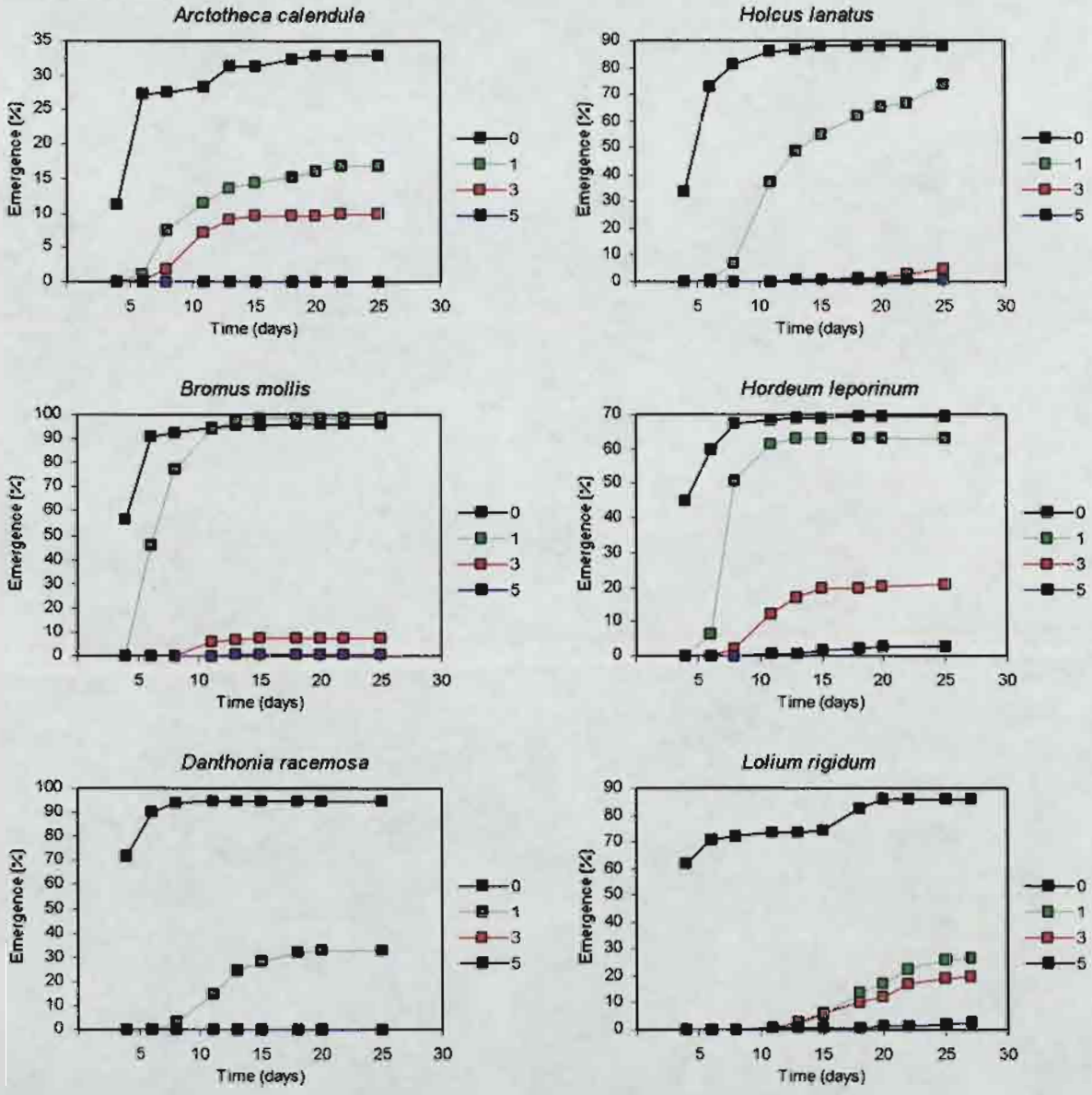


1.2. Experiment 2a: Emergence response to depth of burial

Germination on the soil surface (0 cm) and emergence from 1, 3 and 5 cm were determined for 10 key species. The results are presented in Figure 1.3. The results show that emergence was reduced with depth of burial, and all of the species tested had very low levels of emergence from 3 or 5 cm. Emergence from 1 cm was generally good, but reduced below values of surface germination. This reduction was slight for some species, but substantial for small-seeded species such as *Danthonia racemosa, Trifolium glomeratum* and *Arctotheca calendula*, and *Lolium rigidum*. In contrast, emergence from 1cm was greater than surface germination for *Trifolium subterraneum*. The results for the species have been used to parameterise the germination model and are discussed further in section 2.2.3. In the GRAZPLAN pasture model seeds are assumed to lie in the top 15 mm of soil. This is appropriate for an uncultivated, permanent pasture situation. These results will be used further when the model is extended to account for the effects of cultivation and therefore seed depth on germination and emergence.

Figure 1.3. Surface germination and seedling emergence from three soil depths for ten pasture species.



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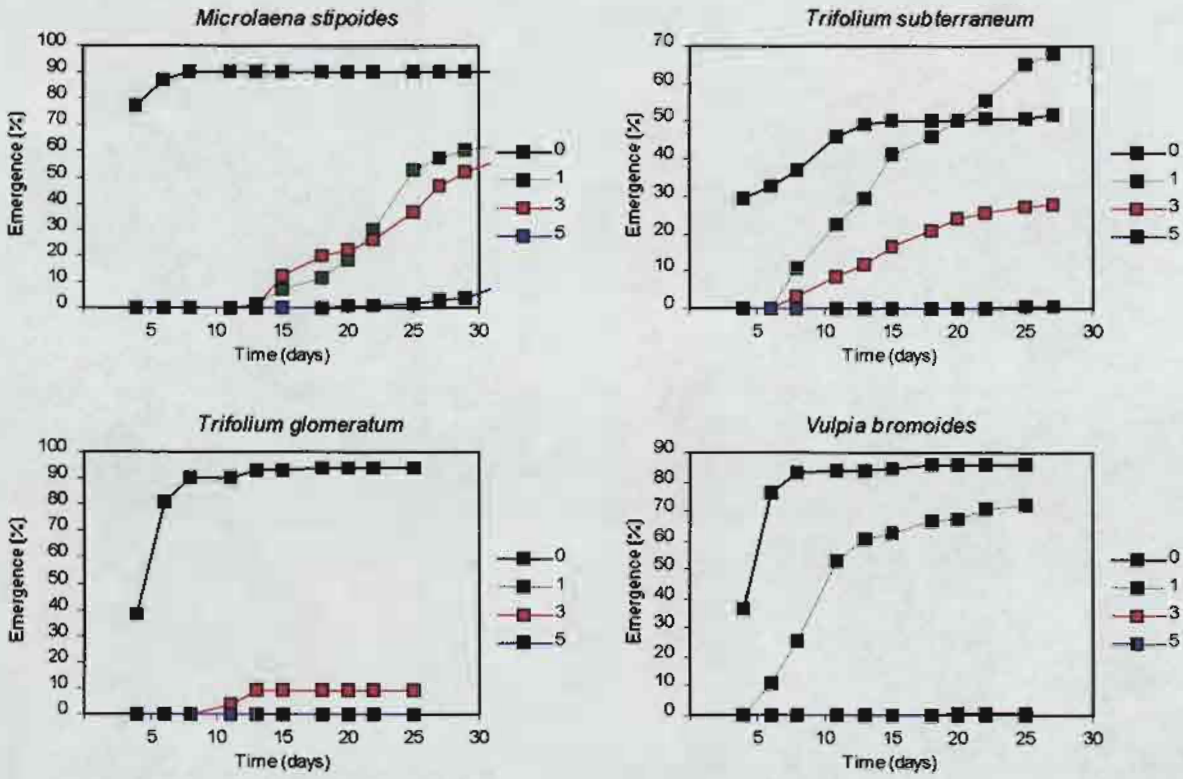
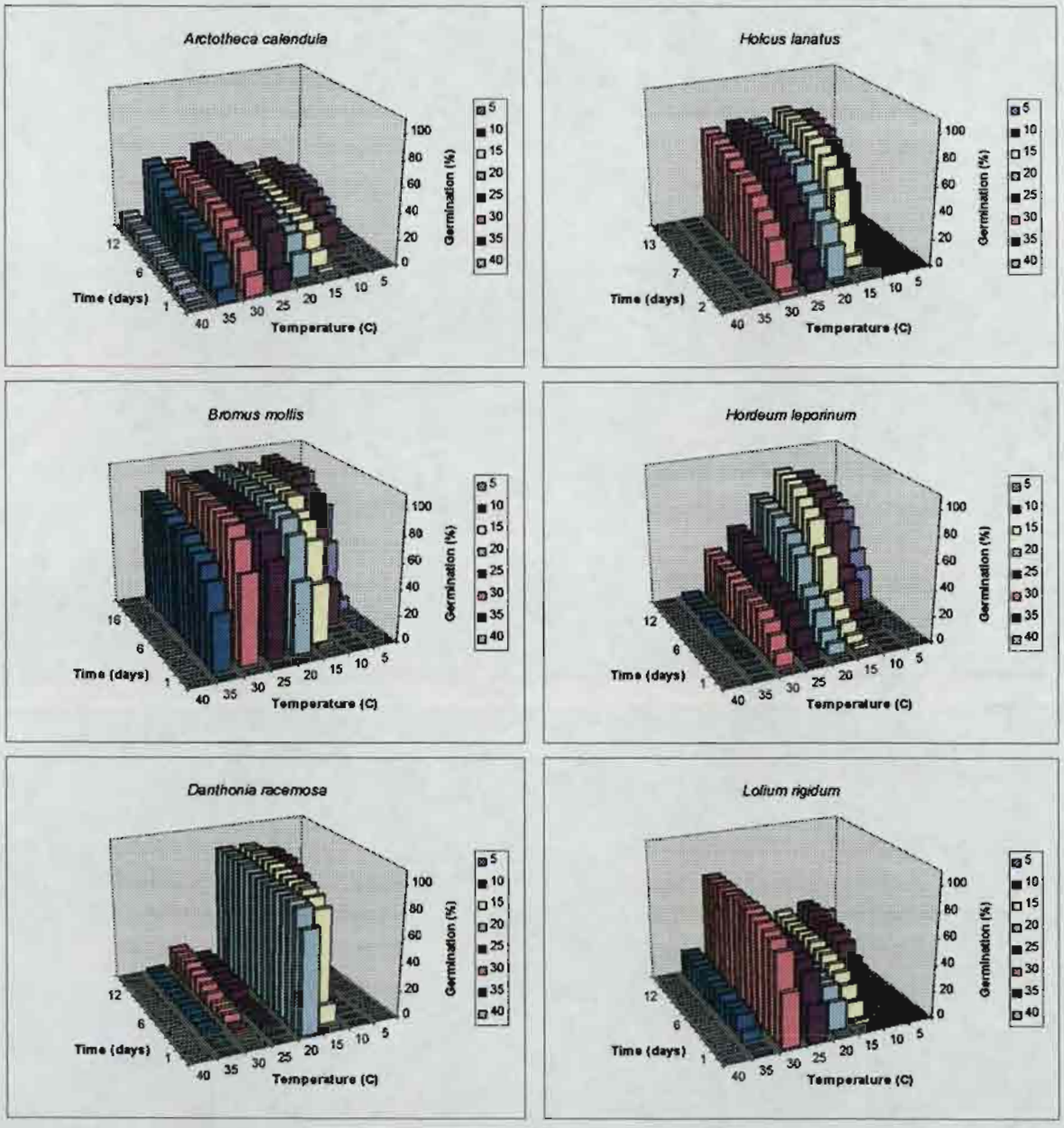


1.3. Experiment 2b: Germination responses to temperature

This series of experiments was conducted on a temperature gradient plate at 8 temperatures (5°, 10°, 15°, 20°, 25°, 30°, 35° and 40°C) covering the biologically and environmentally important range of temperatures. The results are presented in Figure 1.4. The species show differences in the optimum temperature(s) for germination, and the breadth of the optimum germination "window". For example, *Trifolium subterraneum* and *T. glomeratum* had high levels of germination from 5° to 35°C whereas *Danthonia racemosa* had high germination only from 10° to 20°C. There were also species differences in the percent germination at the optimum temperature(s), with several species near 100% in contrast with *Arctotheca calendula* having a maximum germination of about 60%. The data also clearly show the lag in commencement of germination at the lower temperatures (5°, 10° and 15°C). The results are discussed in more detail, with respect to the GRAZPLAN germination model in section 2.2.2.

Figure 1.4. Germination response to temperature for ten pasture species.



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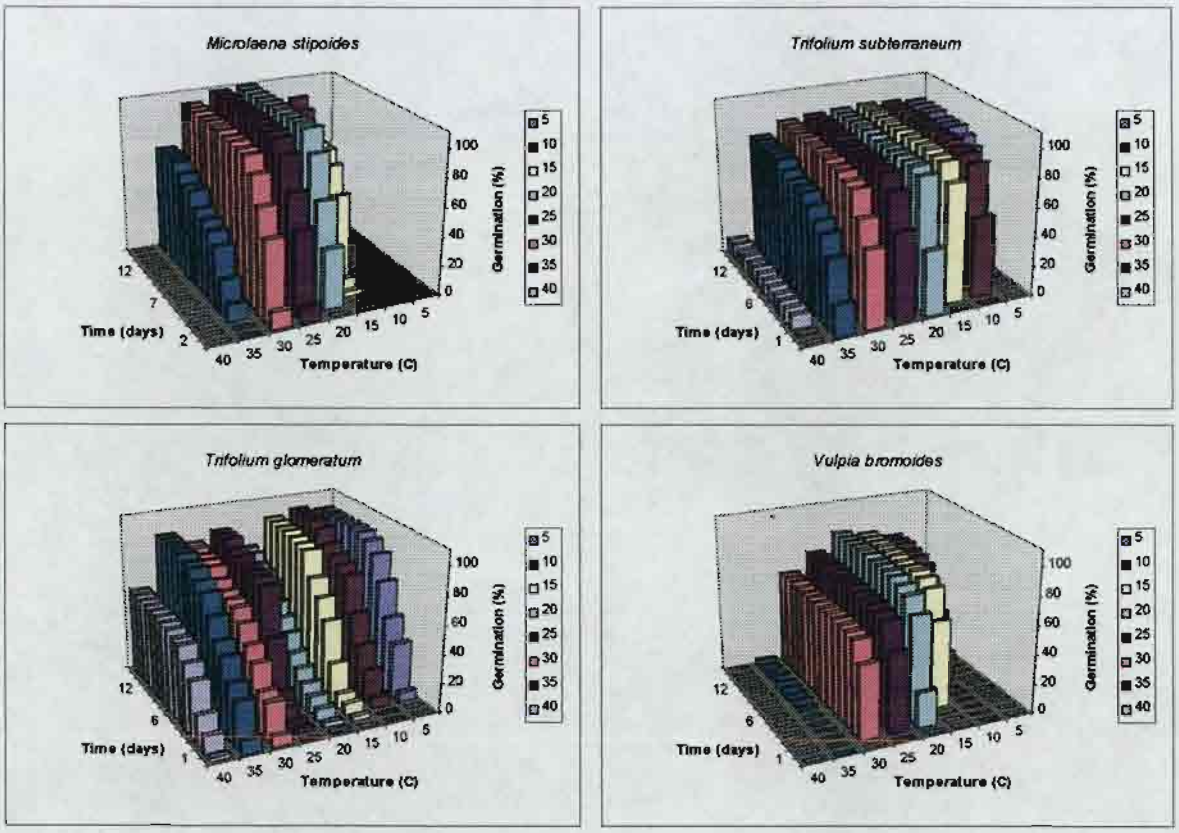
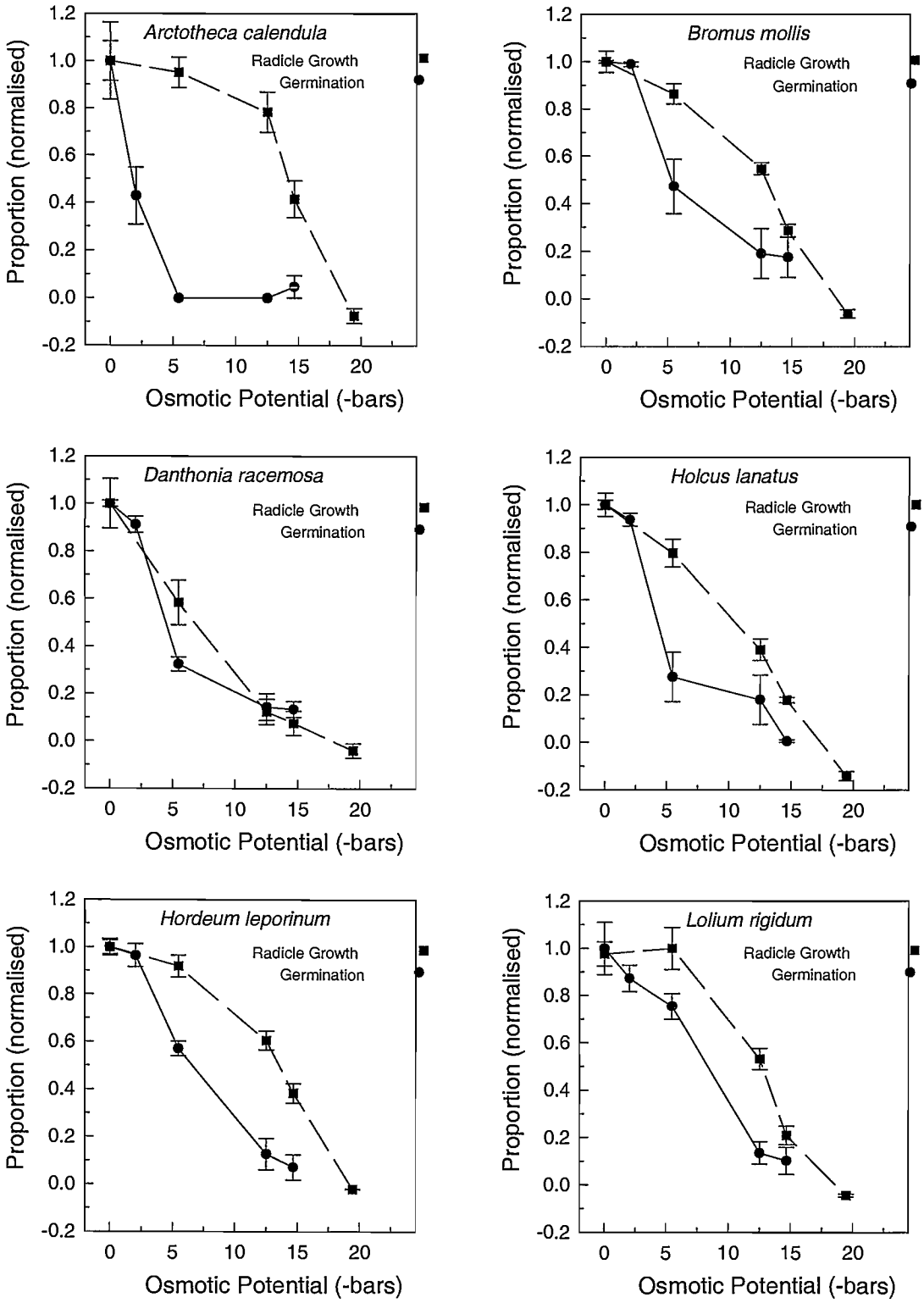


1.4. Experiment 3: Germination and establishment under moisture stress

Ten species were studied to determine their germination and radicle elongation responses to water stress. The species included four annual grasses (soft brome, barley grass, annual ryegrass and vulpia), three perennial grasses (Yorkshire fog, *Danthonia* and *Microlaena*) two legumes (subterranean clover and cluster clover) and one non-leguminous herb (capeweed). The experiment was split into two logical stages: germination responses to moisture stress, and responses of radicle elongation (after germination) to moisture stress. The scientific literature suggests that in general germination is more sensitive to moisture stress than is radicle elongation after germination. For the germination tests, dry seeds of the ten species were placed on germination pads in petri dishes wetted with solutions of different concentrations of polyethylene glycol (PEG) which provided germination environments of differing water potential. For the radicle elongation tests, the seeds were first germinated in distilled water. Germinated seeds with a small but uniform amount of radicle length were selected and placed in petri dishes with environments of differing water potential as described above.

The results are presented in Figure 1.5. Germination of the grasses was generally more tolerant of low water potential than the dicots. *Microlaena* was by far the most water stress tolerant, particularly at water potentials of -12.5 and -14.7 bars. Of the dicots only subterranean clover showed any significant germination below -2 bars. Radicle growth was generally less sensitive than germination to water stress, in agreement with the literature; *Microlaena* appears to be an exception. The radicle elongation of the three dicots at -12.5 bars seems to be greater than that of the grasses. The germination results are discussed in more detail, with respect to the GRAZPLAN germination model in section 2.2.1. The radicle elongation results will be valuable in improving the seedling survival and recruitment routines in the GRAZPLAN model.

Figure 1.5. Germination and radicle growth as affected by osmotic potential for ten pasture species.



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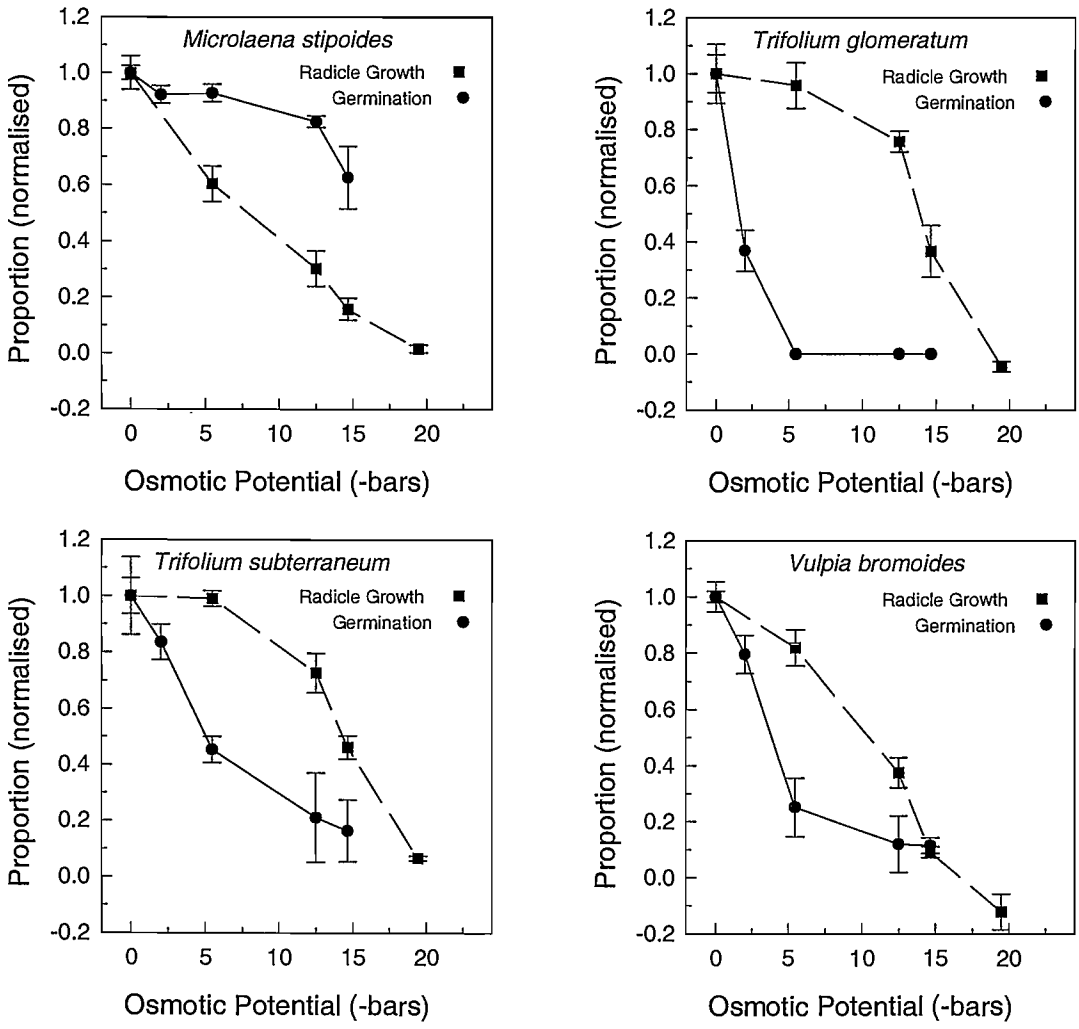


1.5. Experiment 4a: Growth rate and dry matter partitioning

Growth analysis was conducted on species from five "functional groups": native perennial grasses, introduced perennial grasses, annual grasses, annual legumes, and non-legume herbs. Three species were selected to represent each group for a total of 15 species. The relative growth rate (RGR), relative leaf elongation rate (RLER), leaf area ratio (LAR), and net assimilation rate (NAR) were among the growth parameters determined, and their values for the species are presented in Table 1.1. The RGR and RLER varied by more than a factor of 2 among the species. In terms of botanical groups, the native perennial grasses were slow growers, whereas the introduced perennial grasses and annual grasses were fast growers. The herbs showed mixed response with *Emex australis* growing slowly but *Rumex acetosella* and *Arctotheca calendula* having fast growth. The legumes had moderate RGR and RLER. Overall the variation within functional groups was often as great as or greater than that between groups. Final weight was positively correlated with RGR and RLER. RGR was positively correlated with RLER and LAR but not NAR, suggesting the importance of leaf area development and dry weight partitioning to leaves in achieving high growth rates under high nutrient conditions (as were used in this experiment). There was a negative correlation between initial seedling weight and RGR, and this is related to the negative correlation between initial seedling weight and LAR. These negative relationships are in agreement with reports in the literature for other species groupings, and suggest quite dynamic relationships with regard to species competitive ability. Allocation of dry matter to the different plant parts, and particularly to roots and stems for the various species, is discussed with regard to model parameters in section 2.3.1.

Table 1.1. Initial seedling weight, final plant weight, relative growth rate (RGR), relative leaf expansion rate (RLER), leaf area ratio (LAR) and net assimilation rate (NAR) for 15 pasture species in Experiment 4a. The "functional group" of each species is denoted by NPG (native perennial grass), IPG (introduced perennial grass), AG (annual grass), AL (annual legume), and H (non-legume herbs).

Species	Func. Group	Initial Wt (mg)	Final Wt (mg)	RGR (day^{-1})	RLER (day^{-1})	LAR (cm^2/g)	NAR ($g/cm^2/day$)
Arctotheca calendula	H	21	2516	0.143	0.117	154	9.3
Bromus molliformis	AG	16	2234	0.143	0.126	159	9.0
Danthonia richardsonii	NPG	17	912	0.113	0.098	118	9.6
Elymus scaber	NPG	29	1698	0.119	0.103	120	9.9
Emex australis	H	52	1482	0.099	0.063	104	9.6
Holcus lanatus	IPG	11	3247	0.174	0.146	185	9.4
Hordeum leporinum	AG	22	2007	0.132	0.110	170	7.8
Lolium perenne	IPG	19	2363	0.143	0.122	154	9.3
Microlaena stipoides	NPG	22	402	0.080	0.053	149	5.4
Ornithopus compressus	AL	21	1681	0.126	0.116	165	7.7
Phalaris aquatica	IPG	12	1088	0.130	0.096	182	7.1
Rumex acetosella	H	6	890	0.142	0.111	153	9.3
Trifolium glomeratum	AL	4	169	0.116	0.113	130	9.0
Trifolium subterraneum	AL	70	2809	0.107	0.102	112	9.6
Vulpia bromoides	AG	20	1906	0.132	0.134	132	10.0

1.6. Experiment 4b: Maximum rooting depth

Eight species were studied to determine the maximum rooting depth achieved. The species included four annual grasses (soft brome, barley grass, annual ryegrass and vulpia), two perennial grasses (Yorkshire fog and *Microlaena*) one legume (subterranean clover) and one non-leguminous herb (capeweed). The species were grown in PVC cylinders, 200cm long and 10cm in diameter, filled with fine sand and provided with ample water and nutrients. As some of the species were anticipated to root to (or beyond) 200cm, the bottoms were made of clear acrylic so the date at which roots reached 200cm could be recorded. The plants were harvested at flowering, which is when maximum rooting depth is generally achieved in annual species, or after all of the annual species in the case of the two perennial grasses. At harvest, shoots were separated from roots and roots were washed from the sand. Rooting depth and root and shoot dry weights were determined, the percentage roots by dry weight was calculated, and the results are shown in Table 1.2.

Five of the eight species reached a rooting depth of 200 cm. Of these, capeweed was the fastest in about 70 days, followed by annual ryegrass and barley grass (~100 days), soft brome (~130 days) and Yorkshire fog (~140 days). The rooting depths of vulpia, *Microlaena* and subterranean clover were significantly shallower than the other five species (Table 1.2). The root and shoot dry weights, and the proportion of dry weight in roots are also presented in Table 1.2. The most surprising result of this study is the speed at which capeweed roots reached 200 cm. Also somewhat surprising is the shallow rooted nature of vulpia and *Microlaena*. The shallow-rooted nature of subterranean clover is in agreement with previous studies reported in the literature. Data on root distribution with depth are presented in Figure 2.10 in section 2.5. The results for the species have been used to parameterise values for maximum rooting depth and root distribution with depth in the GRAZPLAN model, and are discussed further in sections 2.4 and 2.5.

Table 1.2. Root and shoot parameters from Experiment 4b.

Species	Rooting Depth (cm)	Percent Roots (%)	Root Weight (g)	Shoot Weight (g)
Arctotheca calendula	200	17	14	66
Bromus mollis	200	50	90	87
Holcus lanatus	200	36	97	171
Hordeum leporinum	200	46	60	71
Lolium rigidum	200	21	27	90
Microlaena stipoides	131	25	27	81
Trifolium subterraneum	114	19	21	92
Vulpia myuros	121	35	42	77

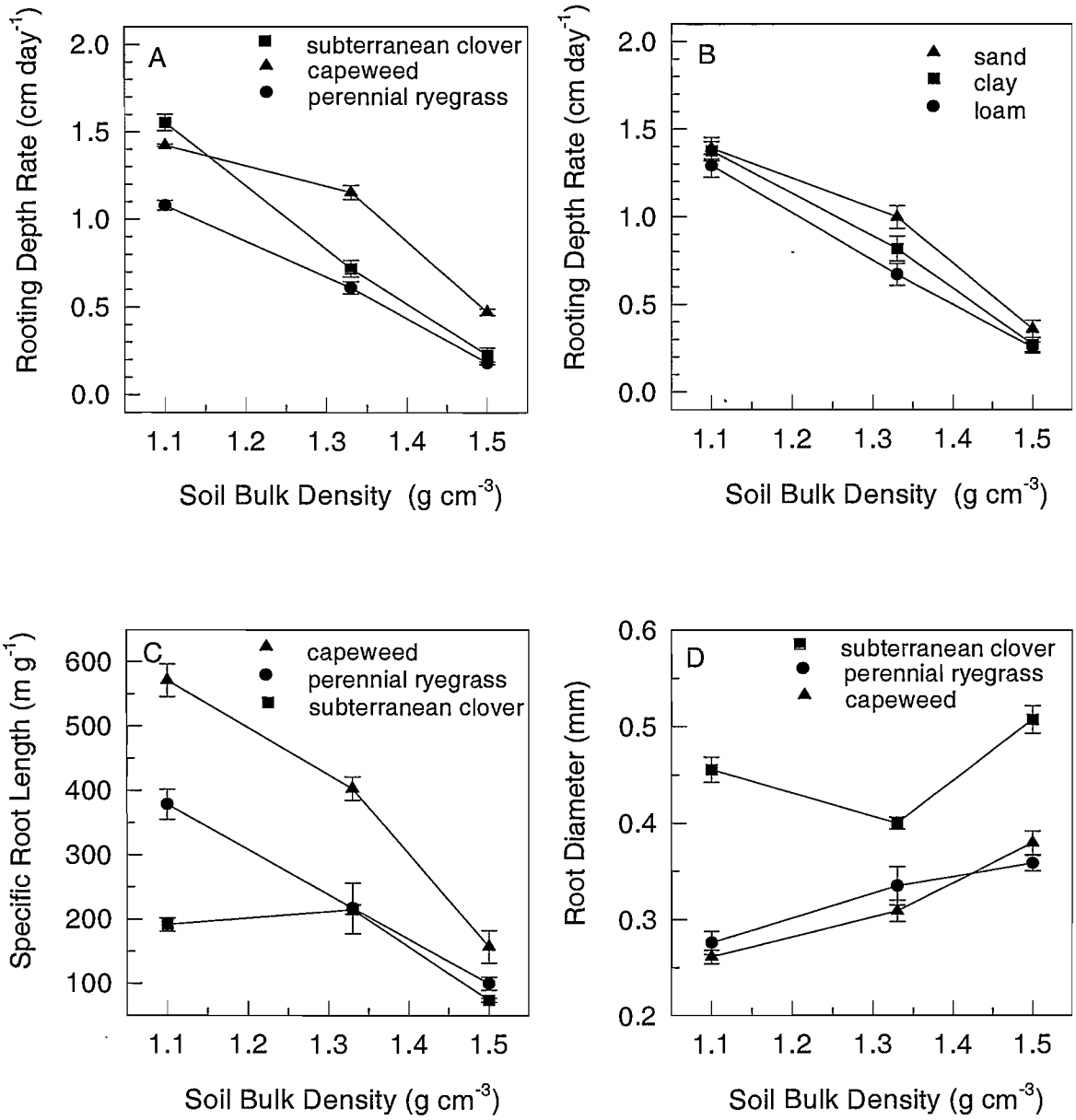
1.7. Experiment 4c: Soil Bulk Density Effects on Root Growth

Three species were evaluated for their ability to develop roots in soils of contrasting bulk density and texture. Three soils (a sand, a clay and a loam) were packed to each of three bulk densities (1.1, 1.3, and 1.5 g cm^{-3}) in PVC cylinders 10 cm in diameter and 20 cm deep. Seeds of subterranean clover, perennial ryegrass, or capeweed were sown into the bulk density x soil type combinations. The experimental design was a 3 species x 3 bulk density x 3 soil type factorial with 5 replicates. The plants were grown in controlled environment growth cabinets which maintained 20°C day/12°C night temperatures and a 12 hour photoperiod. Cylinders were watered daily to 30% volumetric water content, to maintain soil water at a high level of availability but with adequate aeration for unrestricted root growth. Adequate nutrients were provided by watering one day per week with nutrient solution and with distilled water on other days. The cylinders of soil had clear plastic bottoms, and plants were harvested when roots reached the bottom. An exception was for subterranean clover and perennial ryegrass, whose roots never reached the bottom in the high bulk density soils. At harvest, roots were washed free of soil for determination of root characteristics such as specific root length and average root diameter.

The results from the experiment are presented in Figure 1.6. The rooting depth rate was significantly influenced by interactions between species and bulk density (Fig. 1.6A) and soil type and bulk density (Fig 1.6B). At low bulk density subterranean clover, which starts from a large seed, grew roots to 20 cm the fastest. At medium and high bulk density, capeweed roots penetrated much more quickly than the other species. Soil type was only a factor at medium bulk density, where the sandy soil allowed a greater root penetration rate, followed by the clay and then the loam soils. At low and high bulk densities the looseness and tightness of the soils (respectively) overrode any soil texture effects. Specific root length, the length per unit weight of root, generally decreased with bulk density (Fig. 1.6C). Specific root length was greater and decreased more rapidly with bulk density for capeweed as compared to the other species. These declines in specific root length were correlated with increases in average root diameter as bulk density increased (Fig. 1.6D). Root diameter was greater for subterranean clover than for the other two species, which were similar.

In the current version of the GRAZPLAN model, a single equation for rooting depth as a function of bulk density is used for all species. This is due to lack of appropriate comparative data in the literature. This experiment was designed to test the generality of this equation by including plant species and soil texture as treatments. Both of these factors but especially species effects were shown to be important in this experiment. These results have been used to improve the root growth functions in the model, as discussed further in section 2.4. These functions have proven to be important in influencing species composition through their effects on seedling survival, and maximum rooting depth for water uptake during dry periods. The changes in specific root length and root diameter with soil bulk density have major implications for nutrient uptake and will be used to test and parameterise the "NutriAce" nutrient aware version of the model being developed as part of another project.

Figure 1.6. Soil bulk density effects on: A) rooting depth rate by species, B) rooting depth rate by soil texture, C) specific root length by species, and D) root diameter by species.



1.8. Experiment 5: Growth response to nutrients

Eight species were studied to determine their growth responses to additions of phosphorus (P) and nitrogen (N). The species included three annual grasses (*Bromus mollis*, *Lolium rigidum* and *Vulpia bromoides*), four perennial grasses (*Danthonia racemosa, Danthonia richardsonii, Phalaris aquatica* and *Holcus lanatus*) and one legume (*Trifolium subterraneum*). The species were grown in pots in a glasshouse. The pots were filled with 1 kg of a clay loam soil from Ginninderra Experiment Station. The soil was steam sterilised prior to use. (Early in this series of experiments we had trouble getting adequate plant growth at high nutrition. This "suppressive soil" effect, although unidentified, was found to be overcome by sterilising the soil.) Treatments were 6 rates of P at high N and 5 rates of N at high P. Plants were thinned to about 15 to 20 per pot shortly after emergence and the nutrients were then applied. Plants were grown for about 4 weeks after nutrient application and then harvested. The results presented here are for the shoot dry weight as a function of the amount of P or N applied.

Table 1.3 provides an interpretive summary of the results. The two *Danthonia* species gave surprising responses. At low levels of P they did relatively better than many of the other species, as may have been expected. However, the amount of nutrient application required to achieve maximum growth of the *Danthonia* species was very high for P and high for N. This is an interesting result that deserves further attention. Soft Brome had a high requirement for P but the lowest requirement for N of the species in the study. Phalaris had a high requirement for both P and N as expected. Subterranean clover also had a high requirement for P as expected; since it is a legume, it was grown only at the background level of soil N and allowed to nodulate. Annual ryegrass had intermediate requirements for both P and N. Yorkshire fog had the lowest requirement for P with a very flat response to P application, but had a high requirement for N. This flat P response for Yorkshire fog is an interesting finding. Vulpia had low relative requirements for both P and N. It is obvious that the species differ in their requirements for and responses to different levels of P and N. These species-specific nutrient responses could have major implications for competition and changes in botanical composition with different levels of fertility. Because the current (released) version of the GRAZPLAN pasture model does not take into account species specific nutrient responses, these results cannot be directly incorporated. However, they have been influential in the development of a version of the model which takes nutrients into account (see section 3.3) and provide a good base for developing further research into competition for nutrients and its effects on pasture composition.

Table 1.3. Summary of responses in herbage growth after application of P or N to a deficient topsoil.

Species	Function parameters [1]	Relative requirement for P [3]	Relative requirement for N [3]	Comments
Danthonia richardsonii (cv. Tarana)	2.64[2]	very high	high	does better relatively at very low soil P
Danthonia racemosa	2.86[2]	very high	high	does better relatively at very low soil P
Bromus mollis	a = 1.305 b = -0.552 k = 0.061	high	low	lowest N requirement
Phalaris aquatica (cv. Sirosa)	a = 1.848 b = -1.145 k = 0.124	high	high	
Trifolium subterraneum (cv. Goulburn)	m = 0.000 c = 1.793	high [4]	n/d [4]	
Lolium rigidum (cv. Wimmera)	a = 3.049 b = -1.101 k = 0.321	intermediate	intermediate	
Holcus lanatus	m = 0.000 c = 2.734	low	high	lowest P requirement
Vulpia bromoides	m = 0.000 c = 2.194	low	low	

[1] Parameters of alternative functions [yield = $a + b\ e^{-k\ (P_{applied})}$; yield = m (P applied) + c] fitted to shoot yield data to determine maximum yield for normalisation of data.

[2] Highest value used for normalisation of data.

[3] Relative amount of nutrient application required to achieve maximum growth rate

[4] Nodulated plants with zero application of N to the soil

2. PARAMETER FITTING

In this section, data from the experiments described above are used to establish values for species parameters in the GRAZPLAN pasture model. The parts of the parameter set covered are mainly ones which are critical in early-season growth: germination responses, rooting depth (and hence root zone extension rate, given the formulation of the model), and allocation patterns.

2.1. Fitting Techniques

In many cases in the following sections, model parameters have had to be derived from the experimental data by fitting the model equations to the data set rather than by direct estimation. These parameter-fitting analyses have all been carried out using least-squares fitting techniques. That is, for a data set with N observations, parameters for each model have been chosen as those which minimise the mean squared error of prediction, or *MSE*:

$$MSE = \frac{1}{N} \sum_{i=1}^{N} (O_i - E_i)^2 \qquad (1)$$

where O_i is the i-th observation and E_i is the expected value of the i-th observation given the model and a particular set of parameters. This statistic is equivalent to other least-squares statistics such as the root-mean-square error or the error sum of squares in terms of the model-fitting process; it has been used here so that the techniques described by Wallach and Goffinet (1989) for comparing alternative models could be employed on the the root depth distribution data from Experiment 4c.

When comparing model fits across species, it was more appropriate to use the coefficient of determination, *CD*, which is the proportion of the variance in the data set explained by the model. *CD* is analogous to the r^2 value of a regression analysis. Note that a parameter set which minimises *MSE* will also maximise *CD*:

$$CD = 1 - \sum_{i=1}^{N} (O_i - E_i)^2 \Big/ \sum_{i=1}^{N} (O_i - \overline{O})^2 \qquad (2)$$

In most cases, models were calculated and parameters fitted using the optimization capabilities of the Microsoft Excel® spreadsheet. When analysing the root depth distribution data from Experiment 4c, however, jackknife estimates of *MSE* were required; these estimates were computed with a computer program written for the purpose, and the *MSE* values of the alternative models were minimised using the simplex search algorithm of Nelder and Mead (1965).

2.2. Estimation of Germination Parameters (Experiments 2a, 2b and 3)

In the GRAZPLAN pasture model (Moore *et al.* 1997), germination of seeds will only proceed if the surface "available soil moisture" (*ASW*, soil moisture expressed on a scale with wilting point at 0.0 and field capacity at 1.0) is above a species-specific threshold. As long as the soil is sufficiently moist, conditions for germination are monitored by calculating a "germination index" *GI(j)* which mimics the process of imbibition of seeds. Once the index reaches a threshold value, germination begins; the proportion of seeds which germinates on each following day increases, until all remaining soft seeds have germinated. Formally, the germination index and germination rate are calculated on each day of a simulation as:

$$GI(j) \leftarrow \begin{cases} GI(j) + \min\begin{pmatrix} \mathrm{RAMP}(T_{mean}, K_{G2j}, K_{G3j}), \\ \mathrm{RAMP}(T_{mean}, K_{G4j}, K_{G5j}) \end{pmatrix} & ASW_1 \geq K_{G1j} \\ 0 & ASW_1 < K_{G1j} \end{cases} \quad (3)$$

$$\delta B_{germn} = B(j, seed, mature, soft)\,\mathrm{RAMP}(GI(j), K_{G6j}, K_{G7j}) \quad (4)$$

This model has seven species-specific parameters:

K_{G1} (0-1) Threshold available soil moisture below which germination is halted

K_{G2} (°C) Temperature below which gemination is halted

K_{G3} (°C) Lower bound of the optimal temperature range for germination

K_{G4} (°C) Upper bound of the optimal temperature range for germination

K_{G5} (°C) Temperature above which gemination is halted

K_{G6} (d) Time at which emergence commences under optimal temperature and moisture conditions

K_{G7} (d) Time at which emergence is complete under optimal temperature and moisture conditions

2.2.1. Effects of soil moisture deficit on germination

The K_{G1} parameter (the moisture threshold for germination) was estimated from the germination percentage data from Experiment 3 (see section 1.4). First, the water potential values corresponding to each concentration of polyethylene glycol were converted to *ASW* equivalents by assuming a Campbell (exponential) relationship between soil water content and water potential, and making use of the assumption in the GRAZPLAN models that field capacity corresponds to a water potential of -0.3 bar, and wilting point to -15 bar.

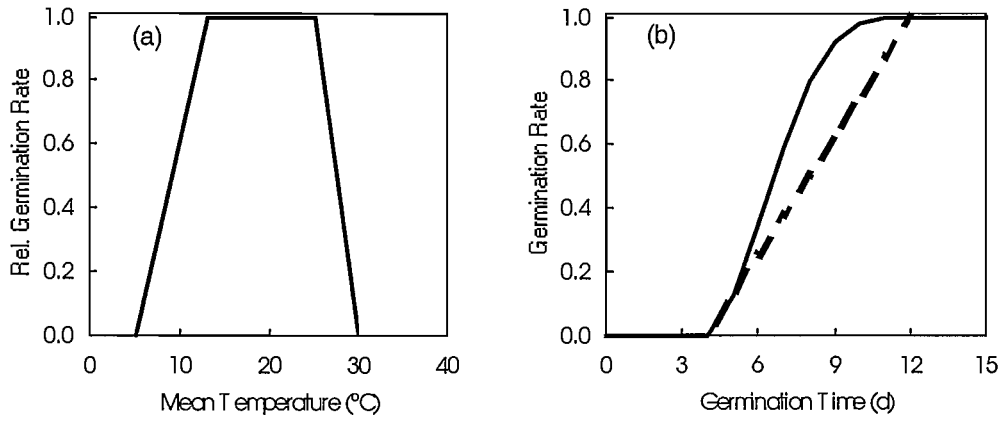


Figure 2.1. Functions describing germination and emergence rate in the GRAZPLAN pasture model:

(a) Effect of temperature on the rate of germination and emergence for a species with K_{G2j} = 5.0°C, K_{G3j} = 13.0°C, K_{G4j} = 25.0°C and K_{G5j} = 30.0°C.

(b) Germination rate under optimal temperature and moisture conditions for a species with K_{G6j} = 4 d and K_{G7j} = 12 d. — — proportion of remaining seeds emerging each day; ——— cumulative proportion of seeds emerging.

Polyethylene glycol level	0	9	16	24	28
Water potential (Ψ, bar)	-0.3	-2.5	-5.5	-14.7	-19.5
ASW equivalent	1.00	0.46	0.26	0.01	-0.07

Inspection of the data showed that germination rates for some species increased over a range of water potentials rather than according to a sharp threshold effect (Figure 2.2), so it was decided to estimate the *ASW* at which germination (totalled over the 22 days of the experiment) reached 50% of the maximum figure, and use this value as the estimate of K_{G1}. Ramp functions were accordingly fitted to the germination data by varying the 50% point and the slope of the increasing portion so as to minimise the *MSE*. The fitted functions are shown in Figure 2.2, and the resulting parameter estimates are given in Table 2.4.

Ramp functions fitted the germination data sets very well. While coefficients of determination for the fitted ramp functions ranged from a high of 97% (for *D. racemosa*) down as low as 56% (for *T. subterraneum*), nearly all the residual variation was within water potential levels (Table 2.1).

Table 2.1. Mean squared errors (*MSE*) achieved when fitting ramp functions of *ASW* to germination data from Experiment 3, and their decomposition into mean squared errors within *ASW* levels (obtained from one-way ANOVA of the data) and the error due to "lack of fit" of the ramp function to level means.

	MSE				*MSE*		
Species	Model	Within	Lack of Fit		Model	Within	Lack of Fit
Arctotheca calendula	0.0003	0.0003	0.0000	*Lolium rigidum*	0.0056	0.0050	0.0006
Bromis mollis	0.0187	0.0186	0.0001	*Microlaena stipoides*	0.0069	0.0064	0.0005
Danthonia racemosa	0.0037	0.0037	0.0000	*Trifolium glomeratum*	0.0048	0.0048	0.0000
Holcus lanatus	0.0131	0.0107	0.0024	*Trifolium subterraneum*	0.0327	0.0285	0.0042
Hordeum leporinum	0.0037	0.0036	0.0002	*Vulpia bromoides*	0.0147	0.0147	0.0000

2.2.2. Effects of temperature on germination time

If the time required for a germinating seed to emerge is temporarily neglected, Experiment 2b (described in section 1.3) allows the estimation of the remaining parameters of the germination model defined by equations (3) and (4). Because measurement intervals varied, the germination data for each species, temperature, time of measurement and replicate were converted to rates of germination (in seeds day^{-1}) so that each measuement would be weighted equally. The parameters of the germination model (together with the number of germinable seeds) were then varied so as to minimise the *MSE* for each species.

The combination of discrete temperature levels in the data set and ramp functions (which have

Table 2.2. Mean squared errors (*MSE*) achieved when fitting the GRAZPLAN germination model to data from Experiment 2b, and their decomposition into mean squared errors within temperatures and times levels (obtained from two-way ANOVA of the data) and the error due to "lack of fit" of the germination model to level means. *CD* is the coefficient of determination, given as a percentage.

Species	*MSE*			*CD*
	Model	Within	Lack of Fit	
Arctotheca calendula	1.88	1.17	0.70	62%
Bromis mollis	7.34	3.84	3.49	84%
Danthonia racemosa	4.97	3.01	1.96	74%
Holcus lanatus	2.89	1.80	1.09	60%
Hordeum leporinum	3.47	2.01	1.45	60%
Lolium rigidum	3.09	1.39	1.70	65%
Microlaena stipoides	8.34	2.95	5.39	68%
Trifolium glomeratum	15.29	10.74	4.56	27%
Trifolium subterraneum	12.52	5.00	7.52	79%
Vulpia bromoides	6.86	4.11	2.76	80%

discontinuous derivatives) in the model meant that there were likely to be local optima in the *MSE* function; the optimization procedure was therefore started several times for each species, with the initial guesses for the temperature parameters being varied systematically. The best parameter estimates are given in Table 2.4 below. Coefficients of determination for each species are given in Table 2.2, and model predictions are graphed against the data (averaged over the replicates) for each species and temperature in Figure 2.3.

The model explains only a relatively small proportion of the variation for *T. glomeratum*, for which it is predicted that there is no temperature dependence at all over the range 5° to 40°; however most of the unexplained variation occurs within time and temperature levels, and so cannot be explained by any model. Leaving *T. glomeratum* aside, the germination model accounts for 60-84% of the variation in the data, depending on species.

It can be seen from Table 2.2 that the "lack of fit" is generally of about the same magnitude as the within-level variation; ideally it should be smaller, but this degree of fit is quite encouraging. The two species showing the greatest relative lack of fit are *M. stipoides* and *T. subterraneum*. Most of the lack of fit in *M. stipoides* is caused by its response at 15°, where germination is slower than at higher temperatures, but where the germination process is faster once it begins. The best-fitting model for *T. subterraneum* predicts that germination rate slows to zero at 35° and 40°, where in reality the rate of germination was no slower but the number of germinable seeds was sharply reduced.

Two modifications to the logic of the germination model were tried to see whether they would improve its predictive ability:

- Based on the observed cause of lack of fit in *T. subterraneum*, a model was tried in which the germinability of seeds was a decreasing ramp function of temperature. Two variants of this model were explored; (i) the threshold values for germinability were set at K_{G4} and K_{G5}, and (ii) the threshold values were allowed to vary freely (thereby adding two further parameters to the model).
- Another model was tried in which the proportion of remaining seeds germinating each day was modelled as being constant rather than as increasing over time. Again, two variants of this model were tried: (iii) the proportion of germinating seeds was set proportional to the rate function used to predict the start of germination, and (iv) the germination proportion was made temperature-independent.

None of these alternative models produced a consistent improvement in the fit of the germination model to the data; in only one out of forty cases (alternative (ii) for *T. subterraneum*) did an alternative model improve the coefficient of determination by more than 5%, and none of the models improved the coefficient of determination of a majority of species by more than 1%. The original germination model has therefore been retained as being the best tradeoff between simplicity and predictive ability.

2.2.3. Delay in emergence with depth of sowing

Experiment 2b measured the time that seeds required to commence germination. In the pasture model, however, "germination" includes the emergence of seeds, which are assumed to lie in the top 15mm of soil. The estimates for K_{G6} and K_{G7} therefore need to be increased in order to account for emergence times. We have decided to use emergence times from the midpoint of the surface soil

Table 2.3. Estimates of emergence time (in days) from 7.5mm depth for ten species, using data from Experiment 2a.

Species	Time at 18°C	T scalar	Time at optimal T	Species	Time at 18°C	T scalar	Time at optimal T
Arctotheca calendula	3.1	0.55	1.7	*Lolium rigidum*	7.7	0.45	3.4
Bromis mollis	2.0	0.54	1.1	*Microlaena stipoides*	14.0	0.58	8.1
Danthonia racemosa	6.8	0.76	5.2	*Trifolium glomeratum*	5.1	1.00	5.1
Holcus lanatus	5.6	0.83	4.7	*Trifolium subterraneum*	8.4	0.58	4.9
Hordeum leporinum	3.3	0.64	2.1	*Vulpia bromoides*	3.8	0.67	2.6

layer (7.5mm), estimated from the data from Experiment 2a, for this purpose. Emergence times have been estimated as the difference between the mean time to germination on the surface and the mean time to emerge from 1cm depth, multiplied by 0.75. Since the average experimental temperature of 18°C was not optimal for all species, the emergence times have then been corrected to give the emergence time at optimal temperature by multiplying by the species' temperature scalar at 18°C. Results are given in Table 2.3.

The variation in emergence time was large; Komogorov-Smirnov tests showed that in most cases the variation could be satisfactorily approximated by a normal distribution. The following procedure was therefore adopted to arrive at final values of the germination time parameters:

(i) the coefficient of variation of the emergence time at 1cm depth was applied to the estimated optimal emergence times from 7.5mm to estimate its standard error;
(ii) a spreadsheet was written which combined the distribution of germination times predicted by the model using the parameters from the previous section with a normal distribution of emergence times for each species.
(iii) the resulting distribution of germination-plus-emergence times was fitted back to the germination model by minimising MSEs.

The data from Experiment 2a will be utilised further when the GRAZPLAN pasture model is extended to account for the effects of cultivation and therefore seed placement on germination and emergence.

2.2.4. Final germination parameter estimates

The final estimates are given in Table 2.4. It should be noted that the germination temperature parameters refer to daily mean soil surface temperatures, where in the published model they referred to air temperatures; this is a change in the model logic. Soil surface temperatures are modelled for this purpose using the logic from the CERES family of crop models.

Table 2.4. Final estimates of germination parameters for ten pasture species. "Start time" and "finish time" are the estimated time to start and completion of germination from analysis of Experiment 2b.

Species	K_{G1} (0-1)	K_{G2} (°C)	K_{G3} (°C)	K_{G4} (°C)	K_{G5} (°C)	K_{G6} (d)	K_{G7} (d)	Start time (2b)	Finish time (2b)
Arctotheca calendula	0.35	3	30	37	39	1.6	5.5	0.4	2.2
Bromis mollis	0.22	6	22	35	39	1.9	4.1	1.0	2.2
Danthonia racemosa	0.24	7	24	35	44	4.5	10.1	0.8	2.3
Holcus lanatus	0.24	2	21	33	33	2.3	5.7	1.4	8.8
Hordeum leporinum	0.24	2	32	35	46	2.5	5.1	0.5	1.3
Lolium rigidum	0.16	8	30	30	35	3.1	5.6	0.2	1.5
Microlaena stipoides	0.03	7	26	30	39	9.2	13.8	1.2	5.0
Trifolium glomeratum	0.38	0	1	49	50	4.3	40.9	0.8	19.5
Trifolium subterraneum	0.50	2	30	30	32	2.4	13.4	0.4	1.0
Vulpia bromoides	0.27	6	24	32	33	2.3	5.7	1.4	2.2

Figure 2.2. Percentage germination as a function of estimated "available soil water" (*ASW*) for ten species in Experiment 3a (□), and ramp functions of *ASW* fitted to these data (—).

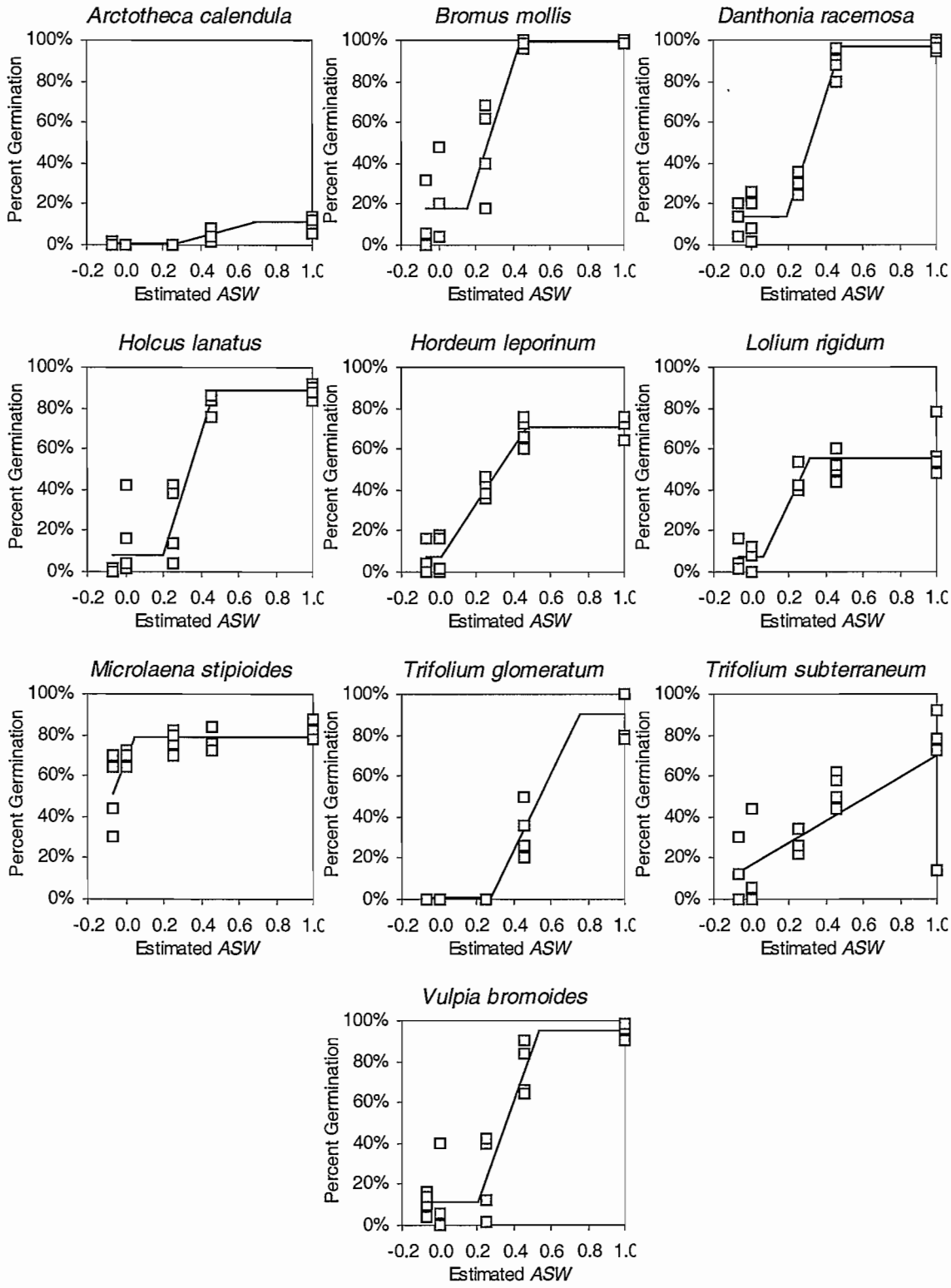


Figure 2.3. Germination rates (in seeds day^{-1}) as a function of temperature and time for ten species from Experiment 2b, and predictions from the GRAZPLAN pasture model fitted to these data. The symbols joined by dashed lines denote the data; the solid lines denote the model predictions.

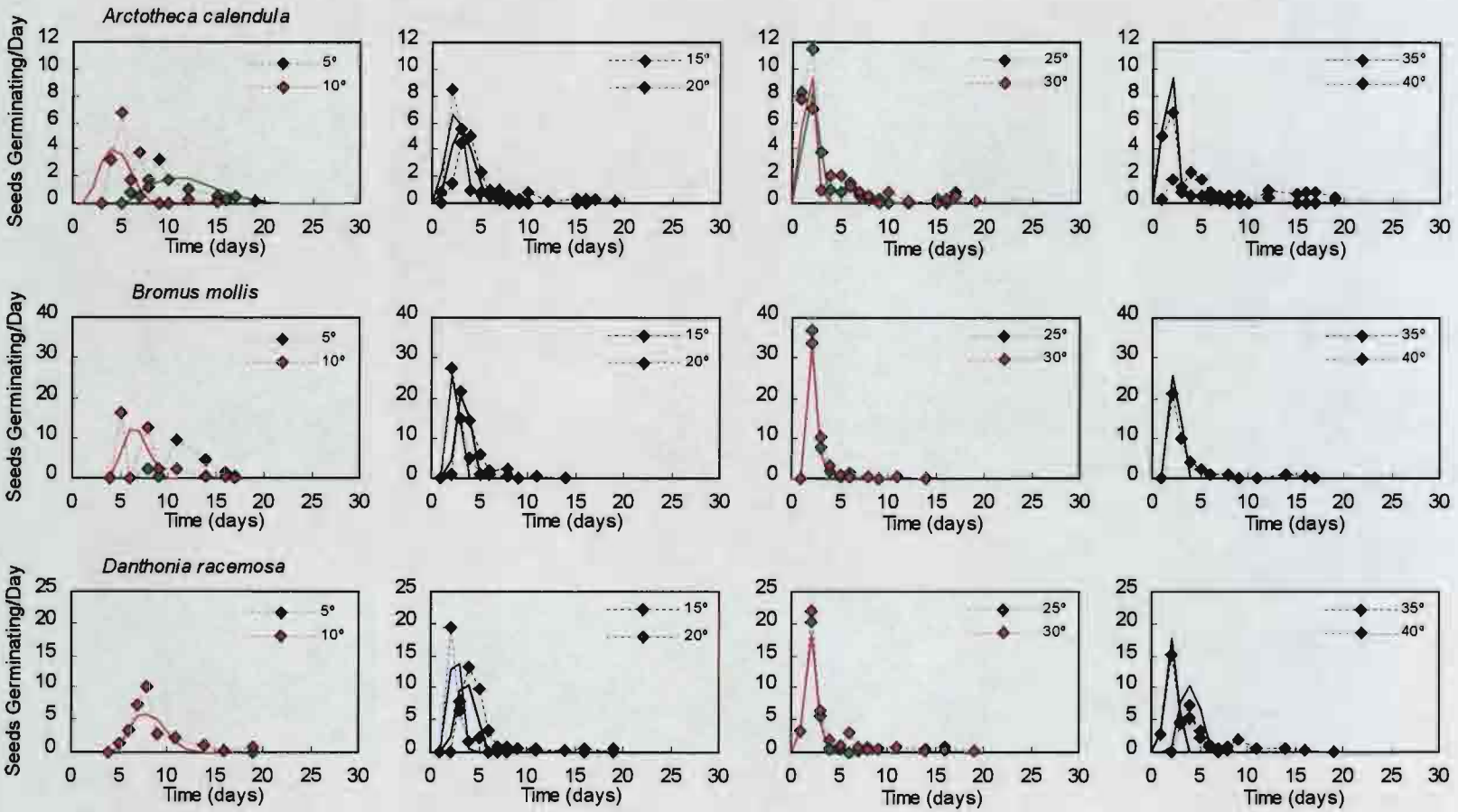


Figure 2.3 (continued)

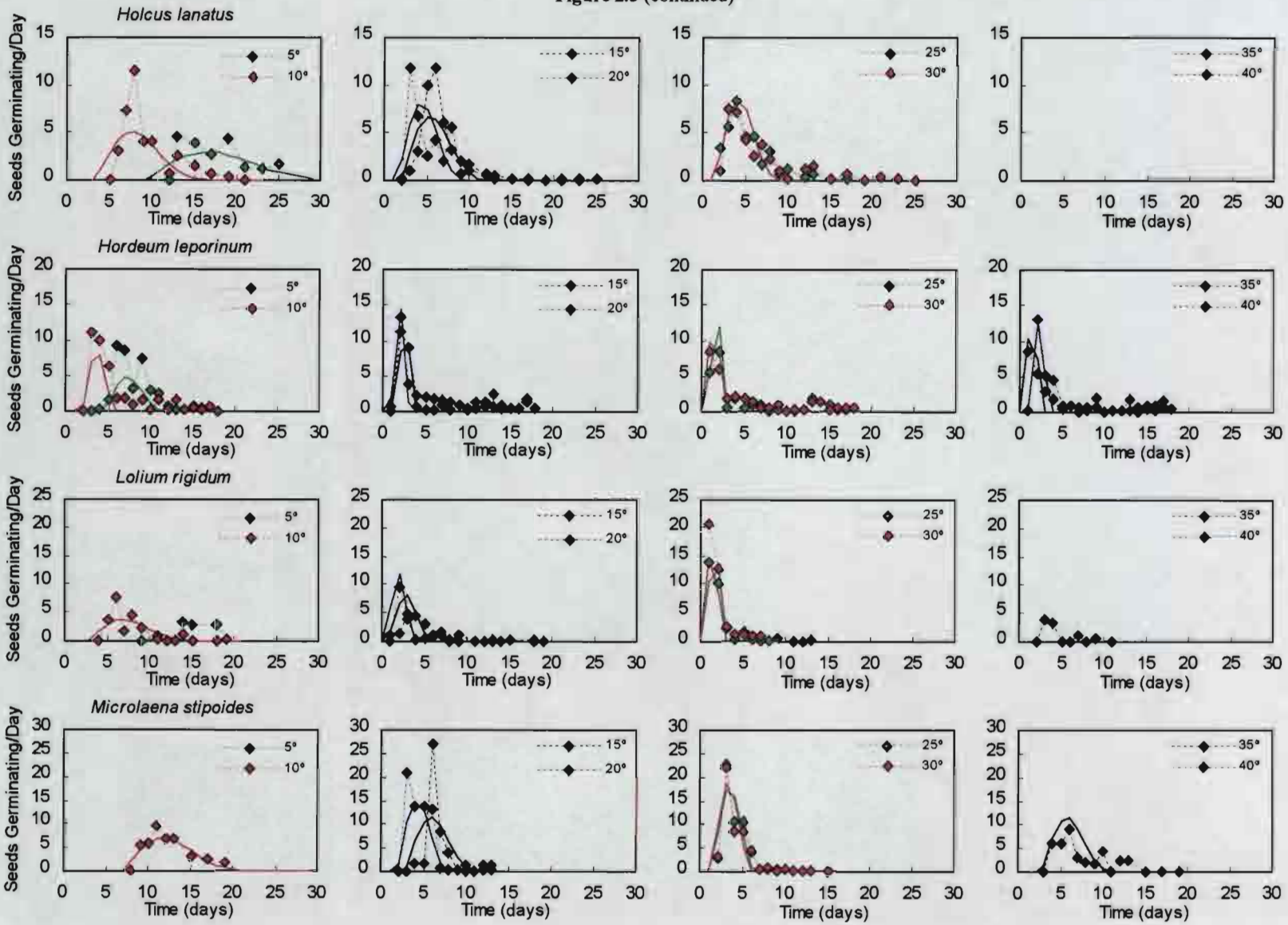
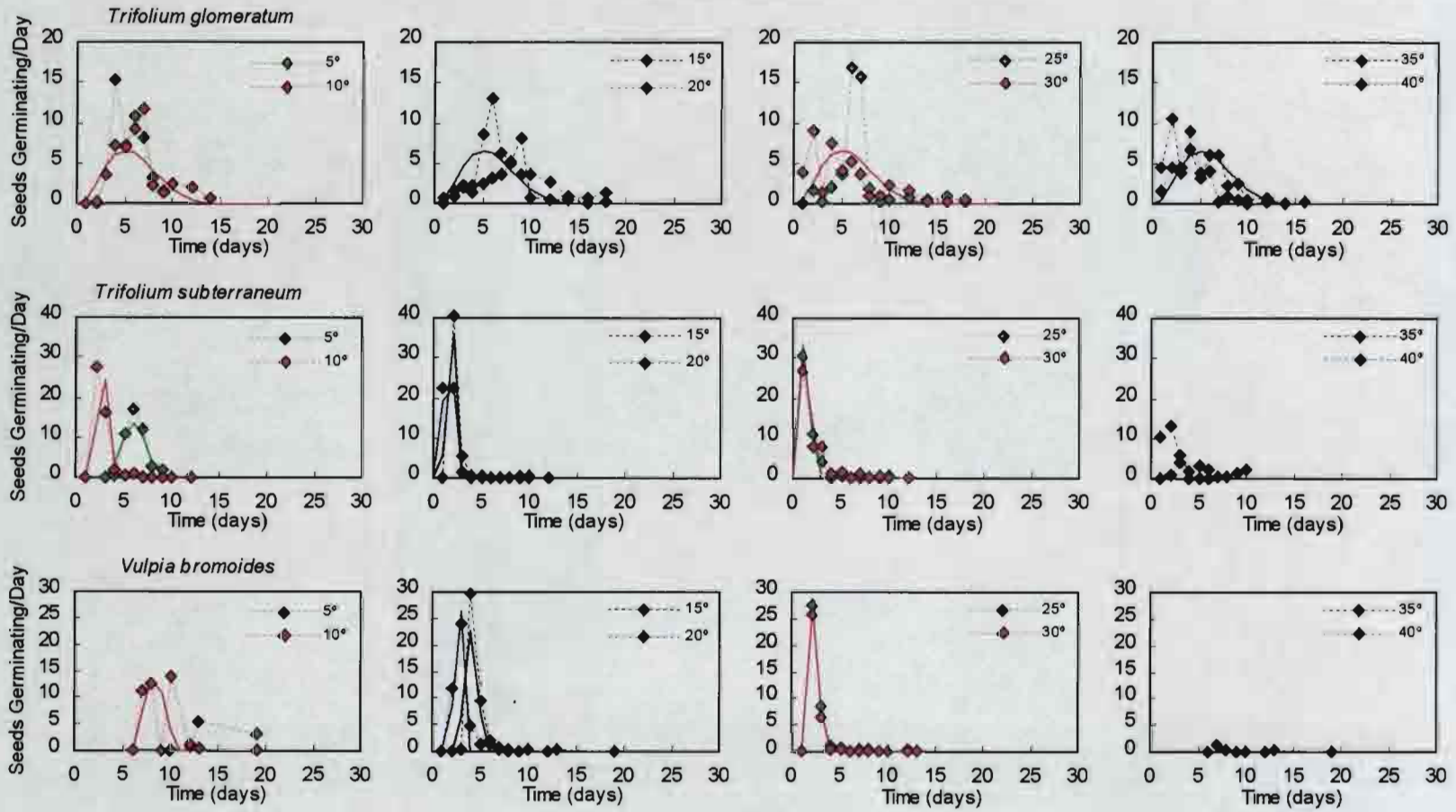


Figure 2.3 (continued)



2.3. Allocation Parameters (Experiment 4a)

2.3.1. Allocation to roots during vegetative growth

One of the key parameters in the model is K_{A1}, the proportion of assimilate directed below-ground during vegetative growth. In order to estimate this parameter, measurements of above-ground and below-ground production during vegetative growth are required. While root and shoot production were measured in several of the experiments presented in this report, Experiment 4a (section 1.5) included the widest range of species and was the only one in which the onset of reproductive growth could be detected; it has therefore been used to estimate values for K_{A1}.

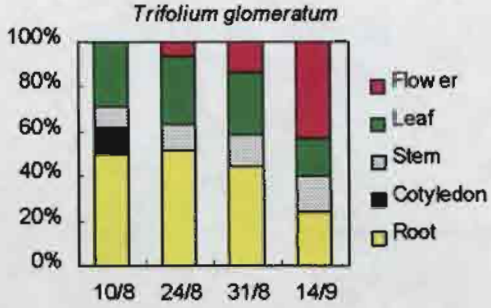


Figure 2.4. Partitioning of total plant mass of *Trifolium glomeratum* grown under ambient CO_2 conditions at four harvest times in Experiment 4a. Note the onset of reproduction before harvest 2.

Inspection of the harvest data showed that a number of species entered reproductive growth during the experiment (e.g. *T. glomeratum*, Figure 2.4). It was therefore necessary to try to detect the shifts in allocation pattern asssociated with the onset of reproductive growth. This was done by:

(i) carrying out a one-way ANOVA of the ratio (root mass):(total plant mass) for each species, using harvest dates as a factor;
(ii) using the error mean squares from the ANOVAs and the T-method (Sokal & Rohlf 1980), the set of harvests for which the root proportion was not significantly different from the first harvest and for which there was no allocation to flowers was determined;
(iii) estimating K_{A1} as the average root proportion over this set of harvests.

The results of these calculations are given in Table 2.5. The range of values is not particularly large (0.34 to 0.56), and the variation within "functional groups" of plants (annual legumes, native perennial grasses etc) is often as great as or greater than that between groups. It should be noted that the allocation parameters for the perennial grasses are almost certainly underestimates for the established swards which are assumed by the GRAZPLAN pasture model, since the respiratory load imposed by the roots of an established sward will be greater.

Table 2.5. Estimates of the below-ground allocation during vegetative growth K_{A1}, based on pre-reproductive harvests in Experiment 4a. Species marked with asterisks are perennial grasses, for which the K_{A1} figure should be regarded as a lower bound.

Species	Harvests Used	Estimated K_{A1}	Species	Harvests Used	Estimated K_{A1}
Arctotheca calendula	1-4	0.43	*Microlaena stipoides**	1-3	0.34
Bromus mollis	1-3	0.39	*Ornithopus compressus*	1-2	0.40
*Danthonia racemosa**	1-2	0.56	*Phalaris aquatica**	1-3	0.42
*Elymus scabra**	1-3	0.47	*Rumex acetosa*	1-3	0.43
Emex australis	1-3	0.47	*Trifolium glomeratum*	1	0.47
*Holcus lanatus**	1-4	0.38	*Trifolium subterraneum*	1-3	0.45
Hordeum leporinum	1-3	0.43	*Vulpia bromoides*	1-3	0.43
*Lolium perenne**	1-3	0.40			

2.3.2. Allocation to stem during vegetative growth

For an ungrazed monoculture of a non-grass species in vegetative growth, the proportion of the shoot allocation which is modelled as being allocated to stem on a given day is given by the following simplification of equation (36) of Moore *et al.* (1997):

$$\frac{A_{stem}}{A_{shoot}} = K_{A4}\left(1 - \frac{1-\exp(-K_{I5}\cdot GAI)}{K_{I5}\cdot GAI}\right) \qquad (5)$$

where K_{I5} is the extinction coefficient under ungrazed conditions, *GAI* is the green area index and the allocation to stem cannot exceed the allocation to shoot.

If it were possible to estimate the time course of *GAI* and shoot dry matter, then K_{A4} could be estimated by fitting the integration over time of equation (5) to the measured stem:shoot mass ratios. Because Experiment 4a used spaced plants rather than swards, however, it is not possible to arrive at sensible estimates of *GAI* (green area per unit ground area); the green areas have been measured, but there is no good way to estimate the ground areas by which they should be divided (Figure 2.5).

Consequently, we have arrived at estimates for K_{A4} values by a simpler and less precise method. For given values of the extinction coefficient, specific leaf area and relative shoot growth rate, the shoot allocation predicted by the model at a given green area is very close to proportional to K_{A4}. If the combined effects of extinction coefficient, specific leaf area and relative shoot growth rate are not too different between species, then it should be possible to arrive at relative magnitudes of K_{A4} from estimates of the stem:shoot mass ratio at a particular green area. We have then converted these relative values back to absolute estimates by using the current value of K_{A4} for *T. subterraneum* (0.5).

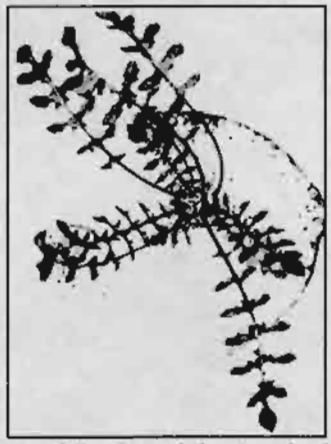


Figure 2.5. One of the *A. calendula* plants before harvest 3 of Experiment 4a. The green area of this plant was measured, but what ground area does it cover?

Only the harvests covering vegetative growth of each non-grass species were used to estimate K_{A4}. After some trial and error, a green area figure of 25 cm² per pot was selected as being within the vegetative growth phase of all species. For each species, the following steps were carried out:

(i) logarithms of the measured green area were regressed against days after sowing (*DAS*), and the average time to reach a green area of 25 cm² was estimated;

(ii) ratios of stem mass to shoot mass were then regressed against *DAS*, and the value of this ratio corresponding in time to a green area of 25 cm² was estimated. Where the regression of the stem:shoot ratio against *DAS* was not significant, the average value of the ratio over all vegetative harvests was used;

(iii) this stem:shoot mass ratio was taken as the relative magnitude of the K_{A4} parameter. The results of this procedure are given in Table 4.3.2.

Table 2.6. Estimates of the stem allocation parameter, K_{A4}, based on pre-reproductive harvests for non-grass species in Experiment 4a. *DAS* denotes days after sowing; *GA* denotes green area per pot; P_{stem} denotes the ratio of stem mass to shoot mass in a pot. The "regression" columns give the significance of the nominated regressions, using the usual notation.

Species	Harvests Used	Regression P_{stem} vs *DAS*	Regression *GA* vs *DAS*	Estimated P_{stem} at *GA*=25 cm²	*DAS* at which *GA*=25 cm²	K_{A4} relative to *Trifolium subterraneum*	Estimated K_{A4}
Arctotheca calendula	1-4	n.s.	***	0.08		0.25	0.12
Emex australis	1-3	***	***	0.26	33	0.81	0.40
Ornithopus compressus	1-2	n.s.	**	0.22		0.67	0.34
Rumex acetosa	1-3	n.s.	***	0.26		0.80	0.40
Trifolium glomeratum	1	n/a	***	0.23		0.71	0.35
Trifolium subterraneum	1-3	n.s.	**	0.32			0.50

2.4. Estimation of Maximum Rooting Depth (Experiments 4b and 4c)

In the published pasture model (Moore *et al.* 1997), the proportion of plant roots in each soil layer m is estimated using an exponential density distribution:

$$\pi_m = \frac{0.01^{\min(\Sigma D_{m-1}/RD,1)} - 0.01^{\min(\Sigma D_m/RD,1)}}{1-0.01} \qquad (6)$$

where π_m is the proportion of roots in soil layer m and ΣD_m is the depth from the soil surface to the bottom of soil layer m. The rooting depth of established plants, RD, is a species- and soil-specific input parameter. In the GrassGro decision support tool, RD for each species is estimated from the bulk density of the soil layers, and from a species-specific scalar, $RD_{max,j}$. The rooting depth predicted for any given species varies linearly with the RD_{max} parameter and quadratically with soil bulk density.

Experiment 4b (see section 1.6) provided an opportunity to estimate relative values for the RD_{max} parameters, at least for the annual species. All other things being equal, the maximum rooting depth of a species in a given soil should be proportional to the rate at which its roots penetrate through the soil profile, i.e. the rate at which the root front advances; and this rate was measured in the experiment.

Formally, RD is estimated in GrassGro as the depth for which

$$\int_{z=0}^{RD} \frac{1}{RRE(z)}\,dz = RD_{\max} \qquad RRE(z) = \max\left(0, 0.95 - 1.5\left[BD(z) - 0.98\right]^2\right) \qquad (7)$$

where RRE is the "relative root extension" and BD is soil bulk density in g cm^{-3}. Equation (7) is based on an analysis of root extension rate data in Cornish *et al.* (1984), and assumes that (i) all effects of soil texture are accounted for by bulk density, and (ii) all species' roooting depths respond to soil bulk density in the same way.

The results of experiment 4c showed that neither of these assumptions hold (Figure 2.6). Before using the root extension rate data from Experiment 4b to estimate rooting depths, therefore, it was necessary to derive a different model for the $RRE(z)$ function which was consistent with the data from both experiments 4b and 4c. Jones (1983) analysed a variety of root activity data (for crops such as maize and soybeans) and concluded that the threshold bulk density at which root activity was optimal, and the bulk density at which it was 20% of optimal, could both be predicted by linear functions of the fraction of silt+clay in the soil. Further, the slopes of the two lines were not distinguishable (Figure 2.7). Since the fraction of sand and the fraction of silt+clay add to one, the results of Jones (1983) can be represented by the following model for $RRE(z)$:

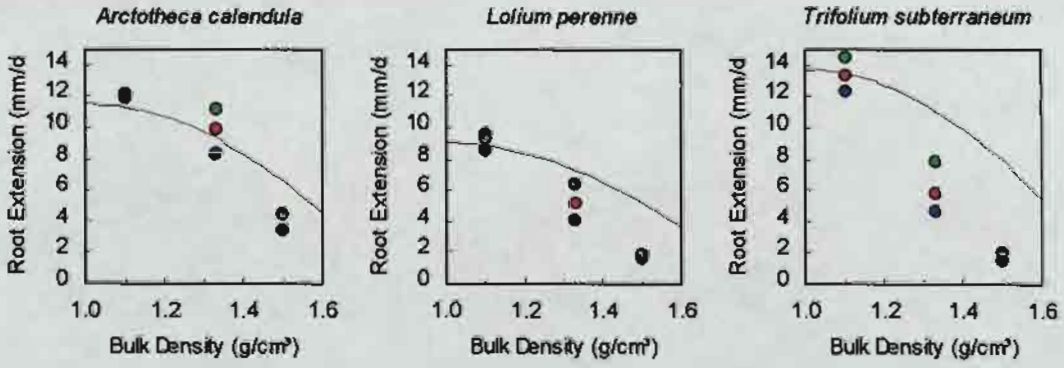


Figure 2.6. Rates of root front extension measured for three species in Experiment 4c, presented as a function of bulk density and soil texture. • sandy soil; • loam soil; • clay soil. The model used in GrassGro for relative root extension (*RRE*) has been superimposed for comparison (—). Note the differences in species' response to bulk density; the generally higher rates of root extension in sands; and the poor prediction of the original model for *RRE*, particularly for *T. subterraneum*.

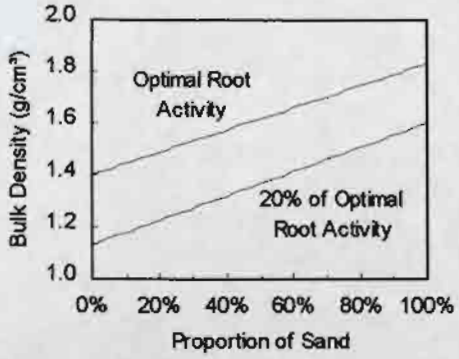


Figure 2.7. Relationships between proportion of sand in a soil and (i) the threshold bulk density for optimal root activity and (ii) the bulk density at which root activity is 20% of the optimal level. From Jones (1983).

$$RRE(z) = \max\left(0, \min\left(1, 1 - \frac{BD(z) - [k_1 + k_2 P_{sand}]}{k_3}\right)\right) \quad (8)$$

where P_{sand} is the proportion of sand in the soil and k_1, k_2 and k_3 are parameters. While Jones (1983) did not distinguish any species-specific effects, the results of Experiment 4c show clear species differences. The model in equation (8) was therefore fitted to the root extension data, keeping k_2 and k_3 the same for the three species but allowing species-specific values of k_1, the threshold bulk density in a soil with zero sand content. Also, the parameter estimates were constrained to be consistent with Experiment 4b by requiring the ratio between the root extension rates predicted for *T. subterraneum* and *A. calendula* for a bulk density of 1.59 and 100% sand to be within 5% of the measured value in Experiment 4b (0.31). The sand content of the three soils was estimated as sandy soil 68%, loam soil 58% and clay soil 43% based on the sand contents of the three parts of the soil mixtures used.

Fitting was done numerically by varying the parameters so as to minimise the *MSE*. Results of the fitting process are given in Table 2.7 and Figures 2.8 and 2.9. The coefficient of determination was 96%.

Table 2.7. Fit of equation 3 to root extension data from Experiment 4c.

Species	k_1	k_2	k_3
Arctotheca calendula	1.09	}	
Lolium perenne	1.00	} 0.20	0.48
Trifolium subterraneum	0.96	}	

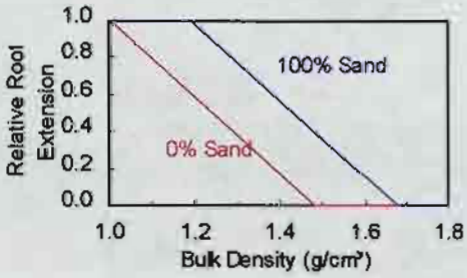


Figure 2.9. Relative root extension rates predicted by equation 8 for *Lolium perenne* at two sand contents.

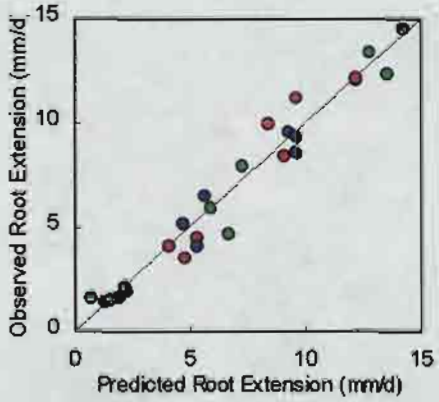


Figure 2.8. Observed root front extension rates from Experiment 4c (means of five replicates) compared with predictions from the fitted model based on equation 8.

- *Arctotheca calendula*
- *Lolium perenne*
- *Trifolium subterraneum*

The new model for rooting depth based on equation 8 requires two species-specific parameters, namely the potential rooting depth RD_{max} and the threshold bulk density k_1. It was only possible to fit one of these parameters to the data from experiment 4b, so it was necessary to try to estimate k_1 values for the remaining species in some other way. It would be expected that a root with a higher specific root length would be able to penetrate soil with higher bulk density and smaller pores; and it turns out there is a good relationship (P = 0.07) between the estimated k_1 values for the three species in Experiment 4c and their specific root length in the weakest soil (sand of bulk density 1.1; Figure 2.6). Because SRL was not measured in Experiment 4b, it has been necessary to infer what the corresponding SRL of other species should be from measurements taken in Experiment 4a; from this, estimates of k_1 for three further species have been obtained. Finally, k_1 for *Lolium rigidum* was arbitrarily assumed to be the same as for *L. perenne*.

Once k_1 values had been estimated, the value of *RRE* could be predicted for each species under the conditions prevailing in Experiment 4b (i.e. bulk density = 1.59, 100% sand). Since bulk density was constant along the soil cores, relative values of RD_{max} could then be estimated by dividing the measured root front extension rates by *RRE*. Finally, RD_{max} for *T. subterraneum* was set to a value sufficiently high to ensure that the observed rooting depths in Experiment 4b could be reproduced.

Table 2.8. Estimates for k_1 and RD_{max} for six species used in Experiment 4b.

Species	SRL in sandy soil (m g^{-1})	Estimated k_1 (g cm^{-3})	*RRE* in Expt 4b	Root front extension in Expt 4b (mm d^{-1})	RD_{max} relative to *T. subterraneum* (mm)	Estimated RD_{max} (mm)
Arctotheca calendula	684	1.09	0.38	28.8	0.90	200
Trifolium subterraneum	192	0.96	0.10	8.9	1.00	220
Lolium rigidum		1.00*	0.19	20.9	1.31	290
Hordeum leporinum	417*	0.99	0.17	20.4	1.43	310
Holcus lanatus	790*	1.10	0.40	15.4	0.46	100
Microlaena stipoides	444*	1.00	0.19	10.1	0.63	140

* Estimated by linear interpolation from SRL data measured in Experiment 4a. *A. calendula* and *T. subterraneum* were used to link the data sets. k_1 for *L. rigidum* was arbitrarily assumed to be the same as for *L. perenne*.

This analysis implies that most of the differences in root growth observed in Experiment 4b are actually due to differential responses to high bulk density, rather than to differences in the maximum root extension rates possible in soils of very low strength. It should be noted that the results for *T. subterraneum* apply only to the cultivar used in the experiment (Mount Barker); it is well known that different cultivars have widely different rooting depths in the same soil (Humphries and Bailey 1961, Hamblin and Hamblin 1985).

2.5. Distribution of Roots with Depth (Experiment 4b)

As described in equation (6) above, the published pasture model assumes that root mass density decreases exponentially with depth. Examination of the root mass x depth data from Experiment 4b suggested that for some species, the assumption of an exponential decline in root density with depth did not hold; there appeared to be proportionately more shallow roots than would be predicted by an exponential model.

This was tested by fitting and comparing two models to the root mass distribution data set: (i) the model given by equation (6), and (ii) a double-exponential model:

$$\pi_m = \alpha \frac{0.01^{\min(\Sigma D_{m-1}/RD_1,1)} - 0.01^{\min(\Sigma D_m/RD_1,1)}}{1-0.01} + (1-\alpha)\frac{0.01^{\min(\Sigma D_{m-1}/RD_2,1)} - 0.01^{\min(\Sigma D_m/RD_2,1)}}{1-0.01} \quad (9)$$

where RD_2 is the maximum rooting depth, RD_1 is the maximum rooting depth of a poplation of "shallow" roots, and α is the proportion of "shallow" roots.

Root organic matter masses in each of the eight sampled soil layers were converted to relative root densities (i.e. proportions of root mass per millimetre of layer depth). The two models were then fitted numerically to the data for each species by varying the parameters so as to minimise the *MSE*. Analysis of variance of the relative root densities showed that there was no effect of CO_2 concentration, so both CO_2 treatments were used in the fitting process. Because parameters were fitted to the data, corrected *MSE* values for each model and species were estimated by jackknifing the data set in a fashion similar to that given by Wallach & Goffinet (1989). Finally, the standard error of the difference between *MSE* values for the two models was estimated (again using a jackknife) and the hypothesis that the double-exponential model provided a better fit to the data – that is, that its corrected *MSE* was lower – was tested using a one-tailed *T*-statistic.

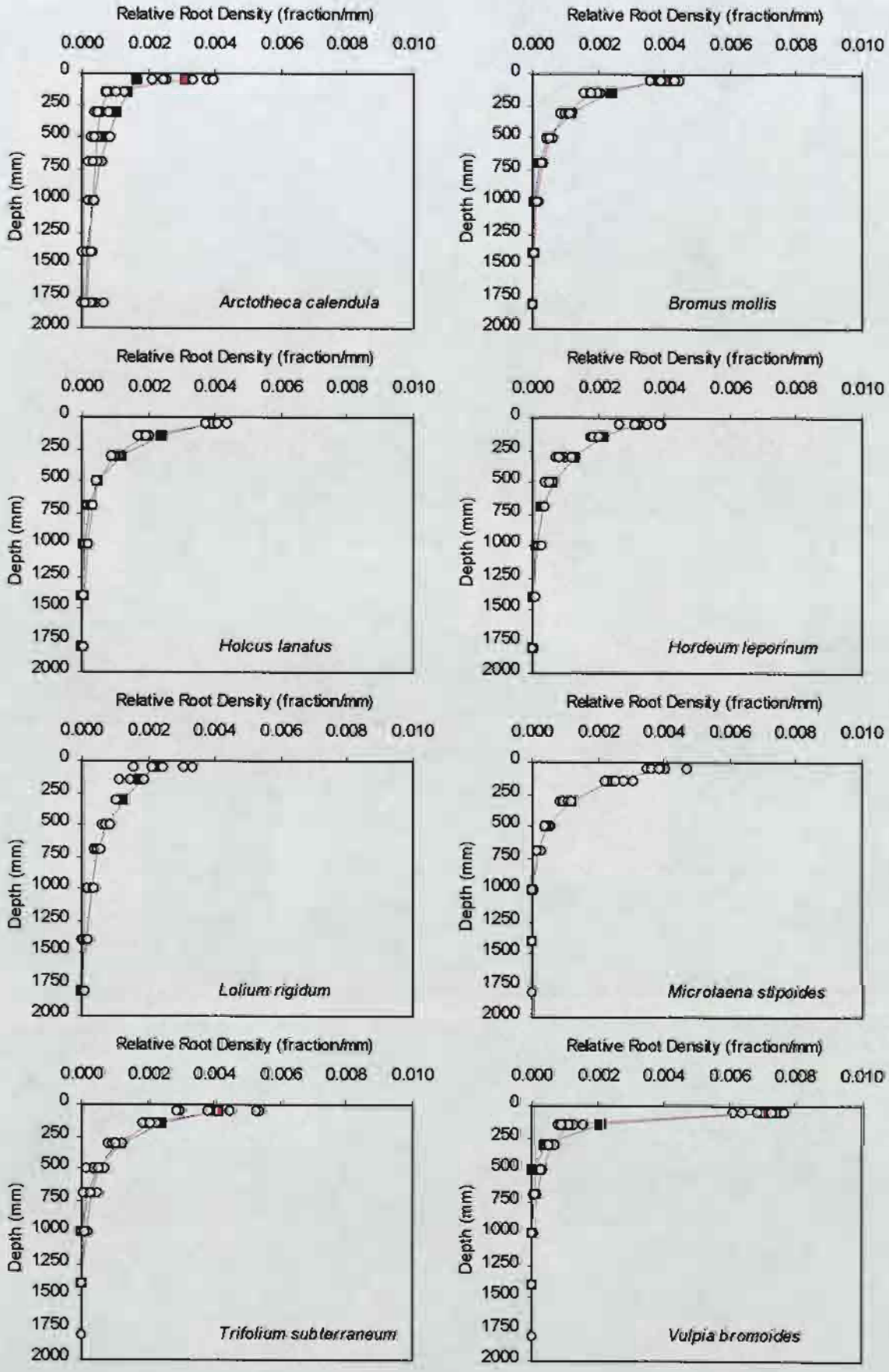
Results of these comparisons in Table 2.9, and the data and models are plotted in Figure 2.10. Five of the eight species show significant departures from the simple exponential model, but only in the case of *A. calendula* and *V. bromoides* is the difference of large size.

The GRAZPLAN simulation model has not yet been altered to reflect the results of this analysis, as distribution of roots within the rooting zone a minor effect on water uptake. Distribution of roots will, however, have a relatively greater effect on nutrient uptake and the location of dead root residues in organic matter cycling.

Table 2.9. Comparison of two models for the distribution of root organic matter with depth

Species	Model 1	Model 2			*MSE* x 10000		S.E. of	
	RD (mm)	α	RD_1 (mm)	RD_2 (mm)	Model 1	Model 2	Difference	
Arctotheca calendula	2625	0.27	185	5200	106.1	30.9	28.8	**
Bromus mollis	953	0.23	240	1480	12.1	2.7	2.5	***
Holcus lanatus	964	0.36	405	1780	11.9	2.4	2.3	***
Hordeum leporinum	1227	0.14	30	1730	18.2	43.7	4.1	n.s.
Lolium rigidum	1850	0.09	305	2120	12.5	10.1	2.8	n.s.
Microlaena stipoides	913	0.76	800	1480	5.9	6.4	0.6	n.s.
Trifolium subterraneum	923	0.15	195	1190	27.1	21.0	3.1	*
Vulpia bromoides	366	0.53	30	1020	23.2	5.7	5.2	***

Figure 2.10. (overleaf) Relative densities of roots of eight species with depth, and fits of the two alternative models for root mass distribution. ○ measurements; ⊣■⊢ Model 1 (simple exponential); ⊣■⊢ Model 2 (double exponential). Model 2 is only shown where it was a better fit than Model 1.


Relative Root Density (fraction/mm)
0.000 0.002 0.004 0.006 0.008 0.010
Depth (mm)
0 250 500 750 1000 1250 1500 1750 2000
Arctotheca calendula
Bromus mollis
Holcus lanatus
Hordeum leporinum
Lolium rigidum
Microlaena stipoides
Trifolium subterraneum
Vulpia bromoides

3. FIELD VALIDATION OF GLASSHOUSE EXPERIMENTS

In this section, data from the experimental stage of the project are validated for a subset of species in grazed pastures under variable grazing and nutrient conditions. This requires using the experimental data in a model context and comparing model simulations against field experimental data to see how well the model simulates competition and botanical composition. We have done this for four field experiments: three from the Temperate Pasture Sustainability Key Programme (Hamilton and Rutherglen grazing management sites) and a phosphorus fertilizer experiment currently being carried out at CSIRO Plant Industry's Ginninderra Experiment station near Canberra. The TPSKP experiments have previously been simulated using GrassGro (Clark 1997) but model predictions of pasture composition were not closely examined.

For all four experiments, pasture dry matter and its composition were measured at repeated intervals, and it is the simulations of these values that are compared against data in this report. Because the animals grazing the TPSKP sites had access to pasture from all treatments, the animal production simulations were expected to diverge from measured values from time to time, and so they are not presented here. In the three TPSKP trials, there were usually a number of minor species present in addition to those which were explicitly simulated; these were combined with their nearest equivalent when computing pasture composition figures for comparison with the model.

Data points are means of two replicates for the TPSKP experiments and three replicates for the Canberra experiment. Statistical analysis of the TPSKP data is still incomplete; confidence limits for the pasture dry matter and composition data from each experiment were therefore estimated by carrying out analyses of variance over all treatments at each measurement time, calculating a standard error from the residual mean square of the ANOVA and applying a *t*-distribution with the appropriate number of degrees of freedom (Sokal and Rohlf 1981). Composition data were arcsine-transformed before the ANOVAs were carried out. We were only able to acquire meaned data for the continuously grazed treatment for the Hamilton TPSKP site (presumably associated with the delay in statistical analysis alluded to above) and consequently we could not compute confidence limits for these data.

3.1. TPSKP experiment - Rutherglen

3.1.1. Specification of the simulated system

Soil parameters used in the simulation were taken from the characterisation carried out as part of the TPSKP, and are provided in Table 3.1. Because the Olsen phosphorus level reported for the site was low, the fertility scalar was set to a value of 0.6. The pasture was simulated as a mixture of phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerata*), annual grasses (as *Hordeum leporinum*) and subterranean clover (*Trifolium subterraneum*). An infestation of loosestrife at the beginning of the experiment was ignored, both in the simulation and in the calculation of actual pasture compositions, since it did not persist and no appropriate parameter set was available. As in the experiment, subterranean clover was sown into the simulation at 10 kg/ha in autumn 1994.

Table 3.1. Specification of the soil used in the Rutherglen TPSKP simulation.

Depth (mm)	Bulk density ($g\ cm^{-3}$)	Wilting point ($mm\ mm^{-1}$)	Field capacity ($mm\ mm^{-1}$)
0-120	1.5	0.09	0.21
120-950	1.5	0.17	0.32

Only the "continuously grazed" treatment was simulated. Small Merino wethers were introduced to the simulation in August 1993 and the stocking rate was then varied to correspond with the actual movements of stock imposed in response to drought conditions. Trial data were available until the end of 1996.

The simulation was begun on 1 January 1993 (eight months before the beginning of measurements) to minimise, as far as possible, the effect of the specification of initial pasture variables on the outcome.

3.1.2. Results and Discussion

The results of this simulation analysis are shown in Figures 3.1 and 3.2. This evaluation of the modified GRAZPLAN model was largely successful. The key features of the pasture dry matter data are reproduced by the model, with the exception of the peak in total dry matter in spring 1994 (the model does, however, correctly predict very little green pasture at these measurement times). The gradual, steady decline in the phalaris content of the pasture is predicted by the model, as is the stable cocksfoot content and the failure of the 1994 clover sowing. The only outcome in the pasture composition data set which is not reproduced by the model is the (re-)appearance of the subterranean clover in late 1995 and its subsequent emergence as a major element of the pasture in 1996. Overall, 84 of the 108 pasture composition data points (78%) fall within the confidence limits of the corresponding measurement.

3.2. TPSKP experiments - Hamilton

Two of the TPSKP trials with different grazing management (the "Delany's sheep" and "Delany's cattle" sites) were simulated at Hamilton. Since they were located close to one another, the same soil and initial pasture specifications were used for both simulations. Only the "continuously grazed" treatment at each site was simulated. Data from each trial were available from September 1993 to August 1995.

3.2.1. Specification of the simulated systems

Soil characteristics used in the simulations were taken from Clark (1997), and are provided in Table 3.2. Because the Olsen phosphorus level reported for the site was low, the fertility scalar was set to a value of 0.65. The pasture was simulated as a mixture of perennial grasses (as *Lolium perenne*), annual grasses (as *Hordeum leporinum*), subterranean clover (*Trifolium subterraneum*) and a variety of broadleaf weeds which were simulated as capeweed (*Arctotheca calendula*).

Table 3.2. Specification of the soil used in the Hamilton TPSKP simulations.

Depth (mm)	Bulk density ($g\ cm^{-3}$)	Wilting point ($mm\ mm^{-1}$)	Field capacity ($mm\ mm^{-1}$)
0-750	1.55	0.17	0.27

In the sheep simulation, small Merino wethers were introduced to the simulation in June 1993 and the stocking rate was then varied to correspond with the actual movements of stock imposed in response to drought conditions. In the cattle simulation, 13-month-old steers were introduced in June 1993 at a stocking rate of 2.0/ha and replaced with 8-month-old steers in January 1994 and again in January 1995.

The simulation runs were begun on 1 January 1993 to minimise, as far as possible, the effect of the specification of initial pasture variables on the outcome of the simulations.

3.2.2. Results and Discussion

The outcomes of these two simulations are shown in Figures 3.3 to 3.6. As in Clark (1997), the simulation of pasture dry matter is very good indeed, particularly for the cattle trial. While the lack of confidence limits precludes a quantitative assessment, the pasture composition predictions do not appear to be quite as accurate as for the Rutherglen experiment: the high clover contents in spring 1994 are not predicted (especially in the sheep simulation) and the model generally has too little annual grass in the cattle simulation. The stability of the perennial grass component is, however, well captured by the model. Although the annual grass, clover and broadleaf weeds showed discrepancies at times, these components generally represented low proportions of the pasture biomass. Typically, low pasture proportions will have large relative errors of measurement and the model may not actually be seriously in error. It is quite likely that the mis-prediction of clover in 1994 is due to relatively low nitrogen availability in a drought year, in which case a version of the pasture model which takes nutrient dynamics into account will be required to simulate it successfully.

3.3. The "Wallaroo 3" experiment - Canberra

Our final validation exercise uses the nutrient-enabled version of the pasture model to simulate both varying grazing pressure and phosphorus nutrition. We have used the results from a continuously-grazed, P-fertiliser experiment being conducted on the Wallaroo 3 paddock at the Ginninderra Experiment Station in the ACT. In the experiment, P is either not applied ("nil" treatment; Colwell available-P about 8) or applied annually at rates intended to achieve Colwell available-P concentrations in autumn/winter of 20-25 mg/kg ("medium" treatment) or 40-50 mg/kg ("high" treatment). Basal dressings of other macro- and micronutrients are applied at intervals to ensure that responses are only to variations in P nutrition. The treatments are grazed with 9 yearling Merino wethers/ha (10 dse/ha; 'district average') or 18 yearling wethers/ha (20 dse/ha). The sheep are replaced annually in March with 6-month old weaners at a typical liveweight of 26 kg.

Four of the treatments have been simulated and are presented in this report: stocking rate (low and high) by fertilizer application (nil and high).

3.3.1. Model structure

For these simulations, the GRAZPLAN pasture and animal models (Moore *et al.* 1998, Freer *et al.* 1997) were linked with a prototype model of nitrogen, phosphorus and sulphur cycling in pastures. This submodel has been adapted from the nutrient cycling model of McCaskill and Blair (1988), and includes representations of organic matter decomposition, urea hydrolysis, nitrification, loss of urine-N through ammonia volatilization, fixation of inorganic phosphorus, fertilizer breakdown and leaching of nitrate and sulphate. Full details may be found in Anon. (1997). Sulphur was eliminated as a factor in the simulations by application of excess sulphate to the system, but nitrogen and phosphorus could become plant-limiting factors.

3.3.2. Specification of the simulated system

Soils. Soil characteristics used in the simulations are provided in Table 3.3. The soil bulk density profile has been averaged over all plots. The soil moisture-related information has been taken from measurements for a yellow podzolic soil in a different paddock at Ginninderra (W. Bond, CSIRO Land and Water, *pers. comm.*). Soil organic carbon levels are means of values measured in 1998 on two of the experimental plots by Dr J. Braschkat (values below 550mm are extrapolated). "Available" phosphorus levels in the 0-100mm layers were estimated by multiplying initial Olsen phosphorus tests by a correction factor of 3.5 and distributing the resulting amount approximately as done by the model. The "fixed" phosphorus pools were assumed to be in approximate equilibrium with the "available" pools. Initial soil nitrate levels were set at arbitrary but plausible levels; the lead-in year of simulation (see below) meant that they had little effect on simulated outcomes.

Pastures. The pasture was simulated as a mixture of phalaris (*Phalaris aquatica*) and subterranean clover (*Trifolium subterraneum*). Parameters governing temperature responses, extinction coefficients, and rooting depths were varied to make the phalaris reflect the more generic mix of

Table 3.3. Specification of the soil used in the simulations.

Depth (mm)	Bulk density ($g\ cm^{-3}$)	Wilting point ($mm\ mm^{-1}$)	Field capacity ($mm\ mm^{-1}$)	Initial values of: Soil organic carbon (%)	Nitrate-N ($mg\ kg^{-1}$)	"Available" phosphate-P ($mg\ kg^{-1}$)	"Fixed" phosphate-P ($mg\ kg^{-1}$)
0-20	1.3	0.08	0.31	2.70	20	50	150
20-50	1.3	0.08	0.31	2.00	20	15	45
50-100	1.3	0.08	0.31	1.43	15	5	15
100-200	1.3	0.08	0.31	0.86	10	1	3
200-300	1.3	0.14	0.23	0.67	2.5	0	0
300-400	1.3	0.14	0.23	0.53	2.5	0	0
400-550	1.3	0.14	0.23	0.24	2.5	0	0
550-700	1.3	0.14	0.23	0.12	2.5	0	0
700-850	1.3	0.14	0.23	0.06	2.5	0	0
850-1000	1.3	0.14	0.23	0.03	2.5	0	0

phalaris and annual grasses that occurred in the pastures. Initial values for key pasture state variables, especially the root reserves of phalaris and the seed pools of clover, were set by first running the model at low stocking rate and fertility for 1992 and recording the simulated values on 1 Jan 1993. All simulations were then run from 1 January 1993, with the stocking rate treatments (but not the fertility treatments) imposed during the pre-experimental year. By this means, the pasture state at the start of the experimental period (March 1994) was largely determined by the model.

Table 3.4. Fertilizer schedule for high fertility simulations.

Date of application	Weight of fertilizer applied (kg ha^{-1})
18 May 1994	350
8 Aug 1995	125
16 May 1996	193
24 Mar 1997	185

Fertility and livestock management. No nitrogen or phosphorus fertilizer was added in the simulations of the nil fertilizer treatment. In the simulations of the high fertility treatment, a fertilizer with 20.7% phosphorus content by weight and an average particle diameter 3.0 mm was added at dates and rates given in Table 3.4.

Medium Merino wethers of age 6 months and weight 26 kg were introduced to the simulated system on 1 March each year and removed on 28 February the following year. The low stocking rate was 9 weaners ha^{-1} and the high stocking rate was 18 weaners ha^{-1}. The animals were fed oats if their condition score fell below 1½. As in the experiment, simulations were destocked between October 1994 and February 1995. Since this livestock regime is only an approximation to the actual animal genotypes and management, results from the animal model are not presented.

3.3.3. Results and Discussion

Figure 3.7 compares simulated and actual available pasture dry matter values for the four treatment combinations. The simulations are generally successful in this respect; the only features of the data which are not captured are the sizes of the spring pasture flush in 1995 (one treatment) and 1996 (both high-fertility treatments).

Predicted and actual clover contents of the pasture are compared in Figure 3.8. The model is less successful in reproducing the clover content data. The broad features of the data set are captured by the model: there is more clover at high fertility, stocking rate has no substantial effect on clover content, and the high clover contents in 1995 are correctly identified. However the absolute values of pasture composition differ from the measured values more often than not, and the model fails to reproduce the trend of increasing clover content over the course of the growing season which is exhibited in nearly all treatments and years. The latter problem is most likely to be due to incorrect specification of either the availability of nitrogen for uptake, or of the response of the phalaris to soil nitrogen. Also, clover contents in the nil-fertilizer treatments - especially at low stocking rate - decline in the model, where in reality they remained low but stable. This error is due to simulated failures of establishment which were evidently not complete failures in the field. The apparently large over-predictions of clover content in winter 1995 in the high-fertility tretments are of less concern, as they represent very small differences in pasture mass.

In summary, the current model is simulating many of the qualitative responses of pasture composition in the Wallaroo 3 experiment, but its quantitative behaviour is not yet adequate. The ability of the soil nutrient cycling model to predict nutrient availabilities, and of the pasture model to predict nutrient uptake rates, are the key limiting areas of the model; work to further improve them continues as part of a separate project.

coefficients, and rooting depths were varied to make the phalaris reflect the more generic mix of phalaris and annual grasses that occurred in the pastures. Initial values for key pasture state variables, especially the root reserves of phalaris and the seed pools of clover, were set by first running the model at low stocking rate and fertility for 1992 and recording the simulated values on 1 Jan 1993. All simulations were then run from 1 January 1993, with the stocking rate treatments (but not the fertility treatments) imposed during the pre-experimental year. By this means, the pasture state at the start of the experimental period (March 1994) was largely determined by the model.

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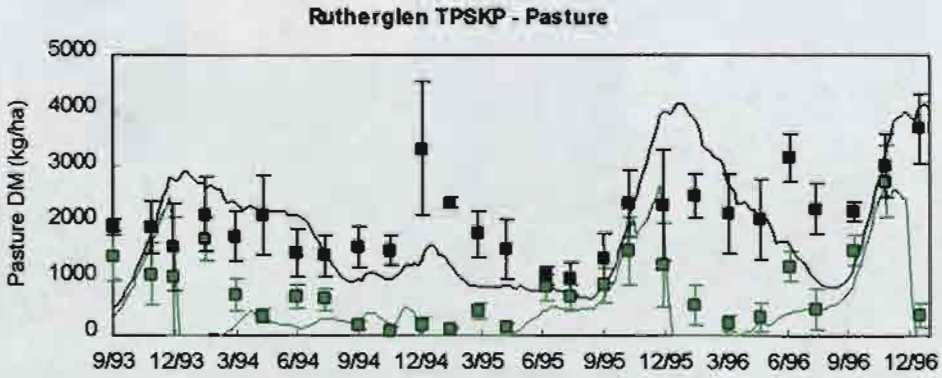

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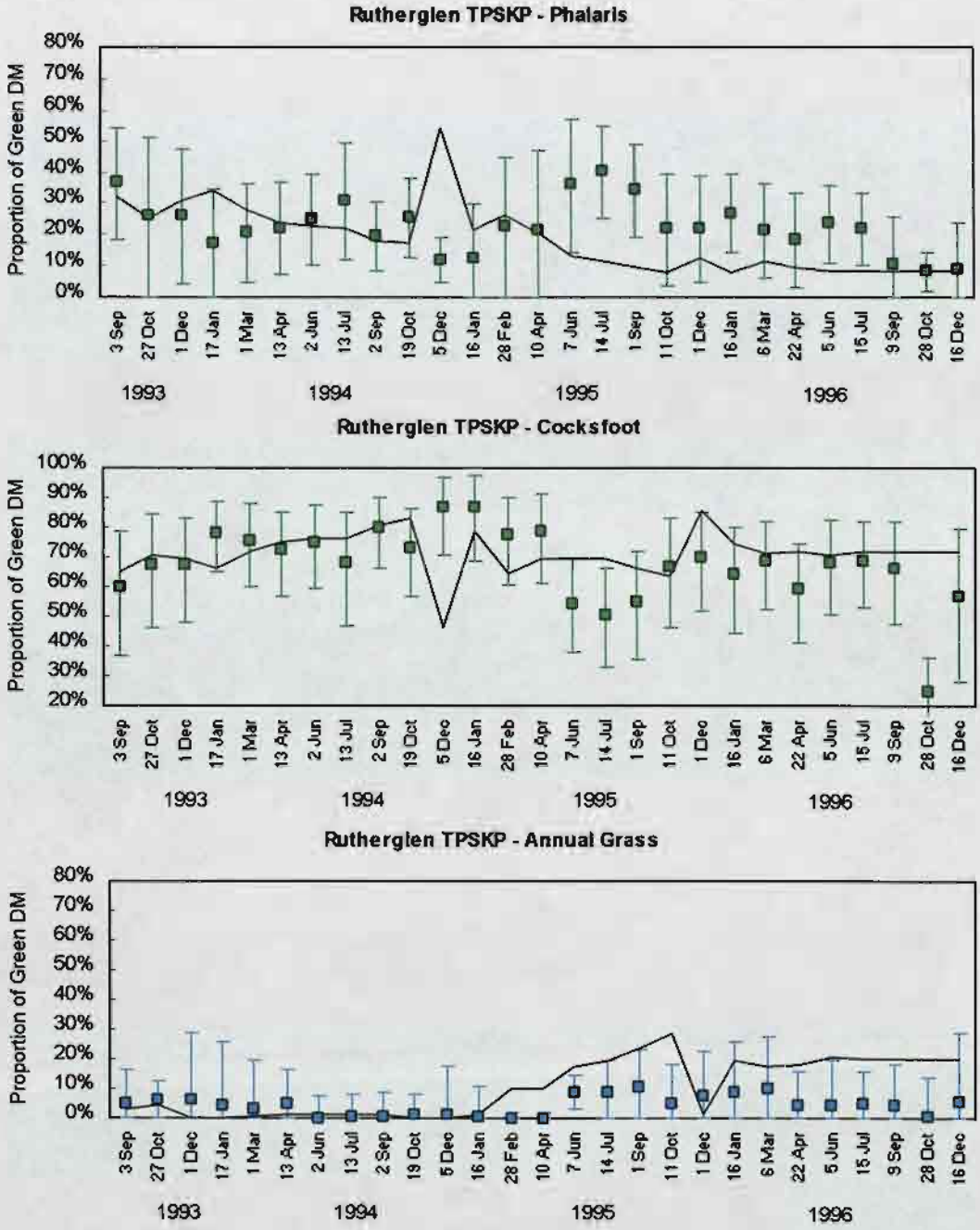


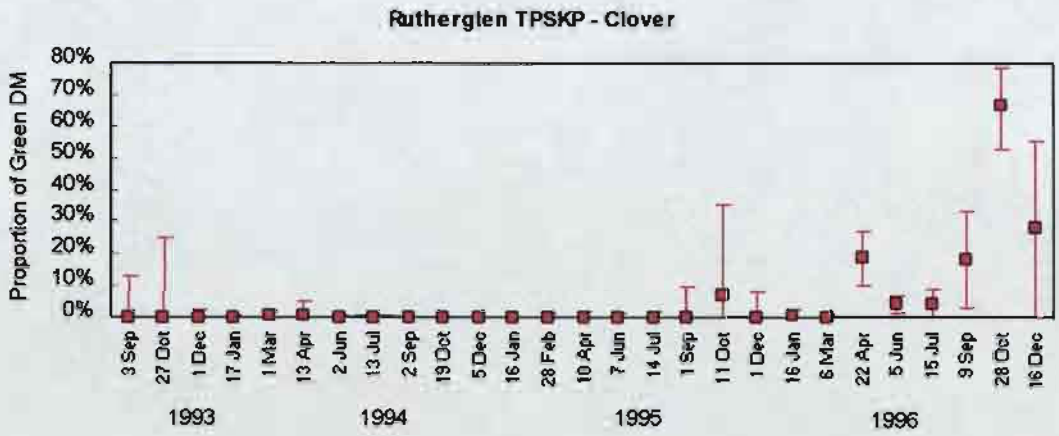

Ruthergien TPSKP - Clover
Proportion of Green DM
80%
70%
60%
50%
40%
30%
20%
10%
0%
3 Sep
27 Oct
1 Dec
17 Jan
1 Mar
13 Apr
2 Jun
13 Jul
2 Sep
19 Oct
5 Dec
16 Jan
28 Feb
10 Apr
7 Jun
14 Jul
1 Sep
11 Oct
1 Dec
16 Jan
6 Mar
22 Apr
5 Jun
15 Jul
9 Sep
28 Oct
16 Dec
1993
1994
1995
1996

Figure 3.3. Simulation of pasture dry matter for the "continuously grazed" treatment of the Delany's sheep (Hamilton) TPSKP grazing management site, using the GRAZPLAN pasture and animal models with the modifications reported in section 2. Symbols represent measured figures for available green pasture (■) while the continuous line (—) shows model predictions.

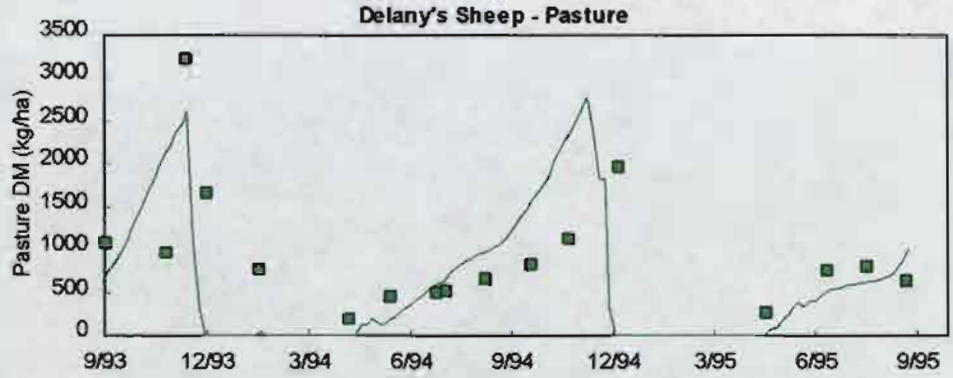


Figure 3.4. Simulation of pasture dry matter for the "continuously grazed" treatment of the Delany's cattle (Hamilton) TPSKP grazing management site, using the GRAZPLAN pasture and animal models with the modifications reported in section 2. Symbols represent measured figures for available green pasture (■) while the continuous line (—) shows model predictions.

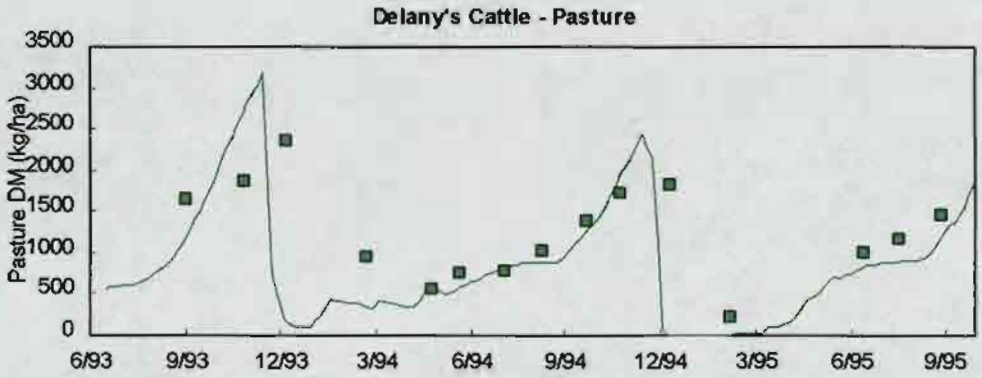
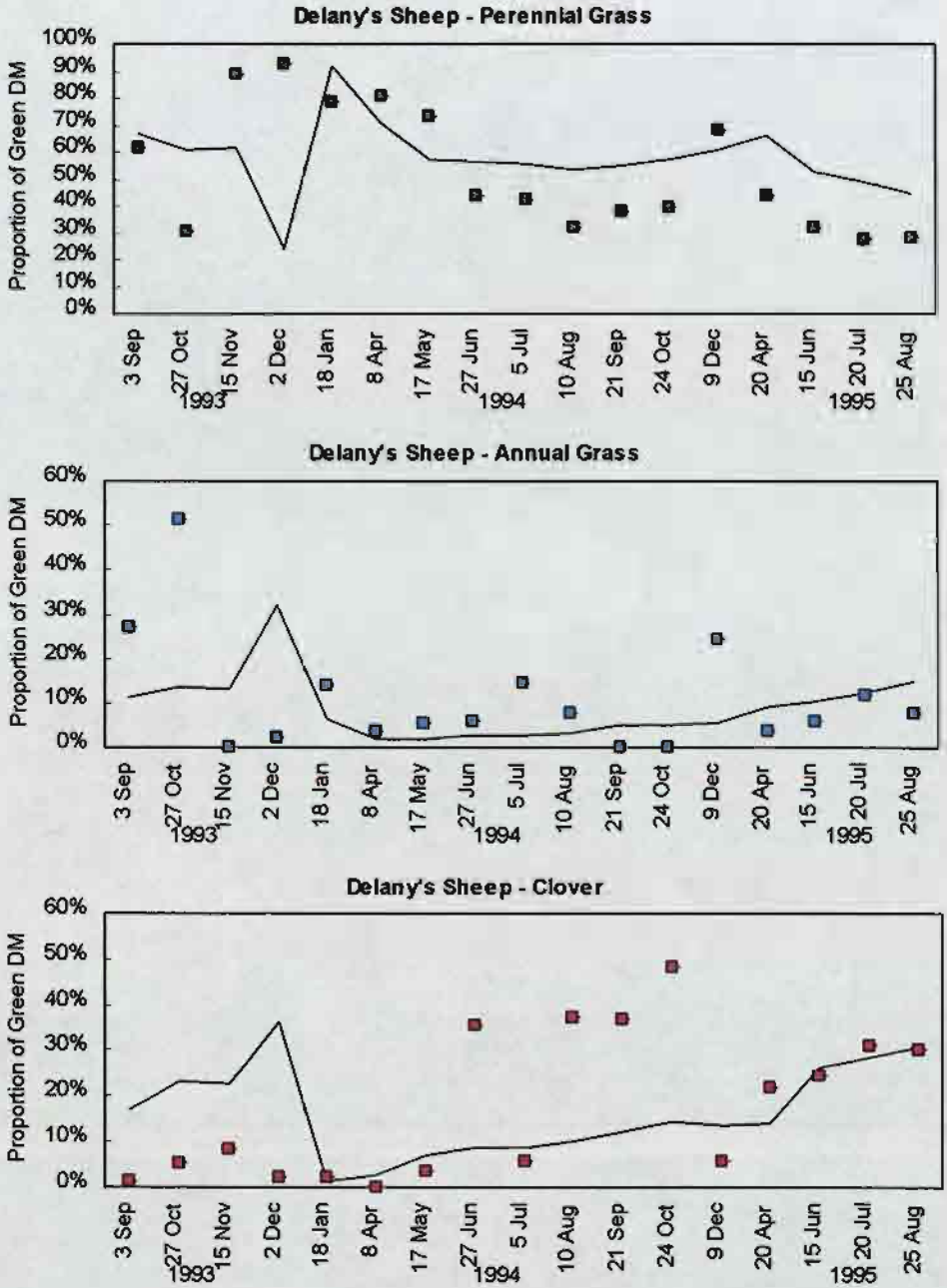
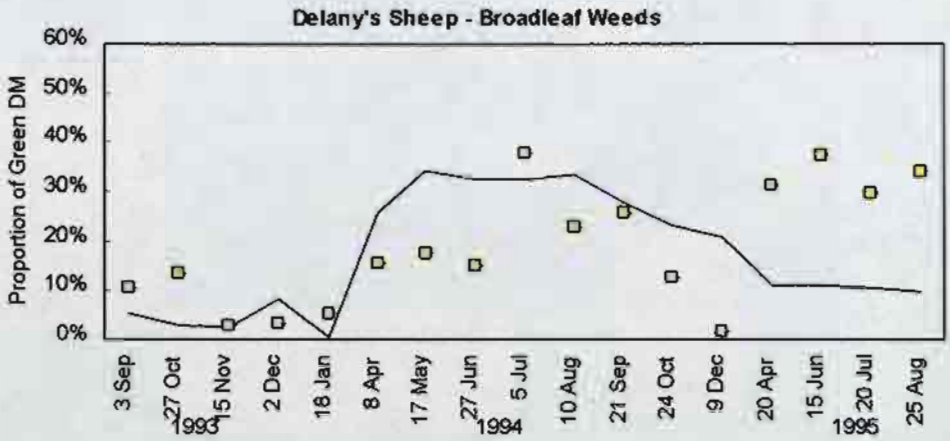


Figure 3.5. Simulation of pasture composition for the "continuously grazed" treatment of the Delany's sheep (Hamilton) grazing management site, using the GRAZPLAN pasture and animal models with the modifications reported in section 2. Symbols represent measured figures for each species' proportion of green dry matter (means of two replicates), with error bars showing confidence limits. Points on the black lines represent the predictions of the model at each measurement time.




Delany's Sheep - Broadleaf Weeds
Proportion of Green DM
60%
50%
40%
30%
20%
10%
0%
3 Sep
27 Oct
15 Nov
2 Dec
18 Jan
8 Apr
17 May
27 Jun
5 Jul
10 Aug
21 Sep
24 Oct
9 Dec
20 Apr
15 Jun
20 Jul
25 Aug
1993
1994
1995

phalaris and annual grasses that occurred in the pastures. Initial values for key pasture state variables, especially the root reserves of phalaris and the seed pools of clover, were set by first running the model at low stocking rate and fertility for 1992 and recording the simulated values on 1 Jan 1993. All simulations were then run from 1 January 1993, with the stocking rate treatments (but not the fertility treatments) imposed during the pre-experimental year. By this means, the pasture state at the start of the experimental period (March 1994) was largely determined by the model.

Table 3.4. Fertilizer schedule for high fertility simulations.

Date of application	Weight of fertilizer applied (kg ha^{-1})
18 May 1994	350
8 Aug 1995	125
16 May 1996	193
24 Mar 1997	185

Fertility and livestock management. No nitrogen or phosphorus fertilizer was added in the simulations of the nil fertilizer treatment. In the simulations of the high fertility treatment, a fertilizer with 20.7% phosphorus content by weight and an average particle diameter 3.0 mm was added at dates and rates given in Table 3.4.

Medium Merino wethers of age 6 months and weight 26 kg were introduced to the simulated system on 1 March each year and removed on 28 February the following year. The low stocking rate was 9 weaners ha^{-1} and the high stocking rate was 18 weaners ha^{-1}. The animals were fed oats if their condition score fell below 1½. As in the experiment, simulations were destocked between October 1994 and February 1995. Since this livestock regime is only an approximation to the actual animal genotypes and management, results from the animal model are not presented.

3.3.3. Results and Discussion

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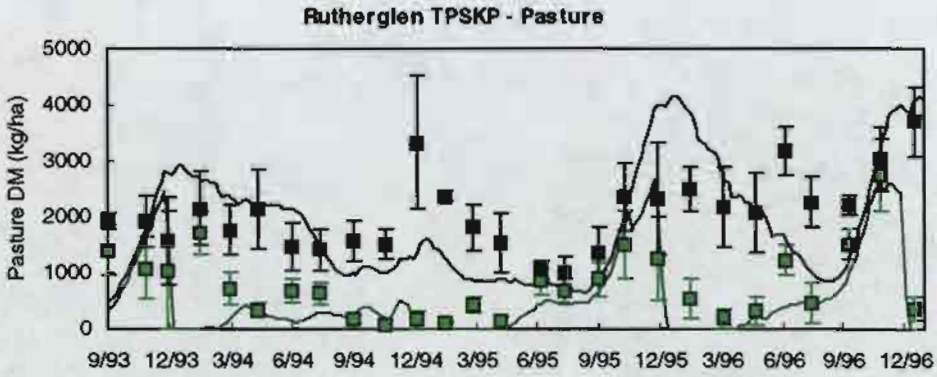

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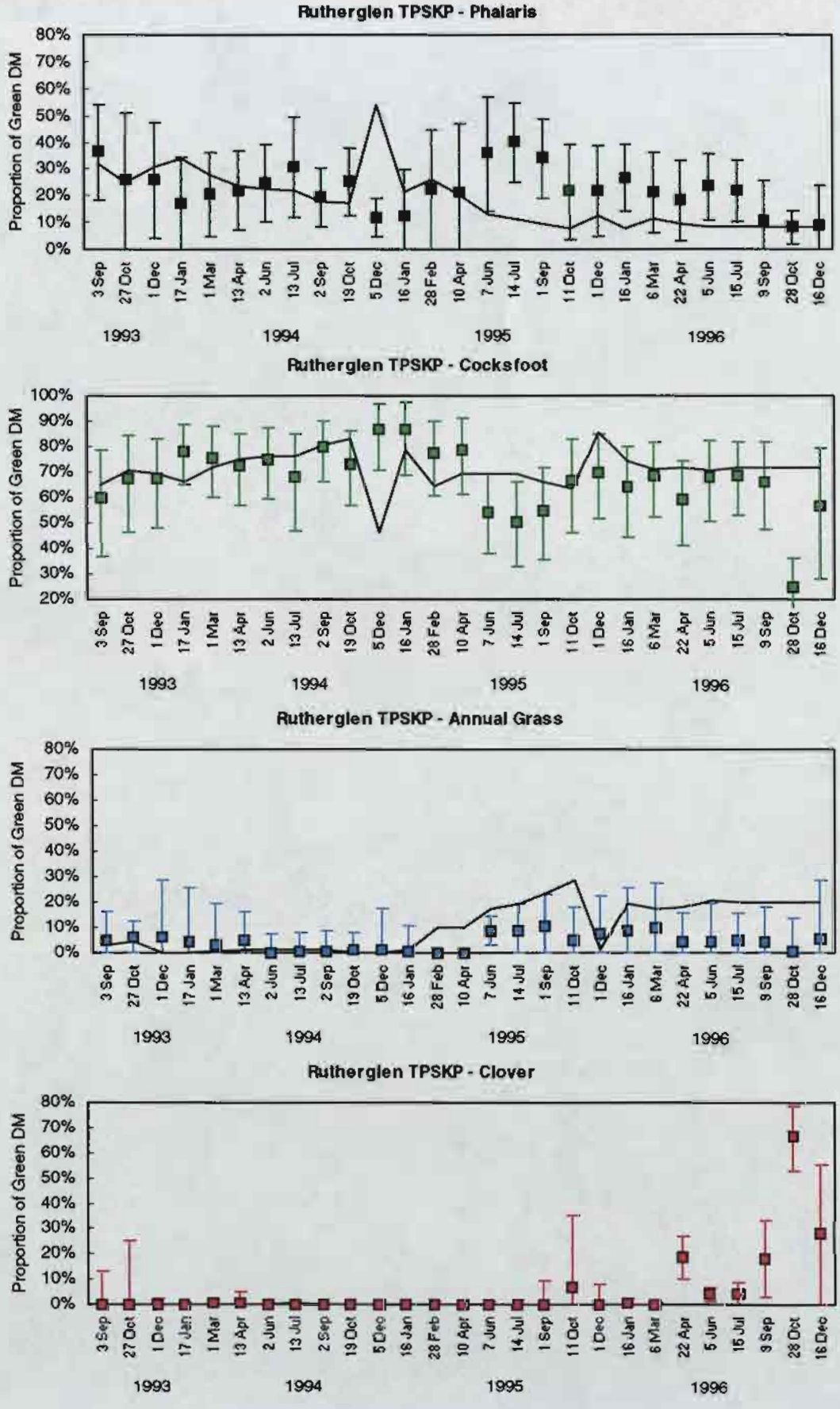

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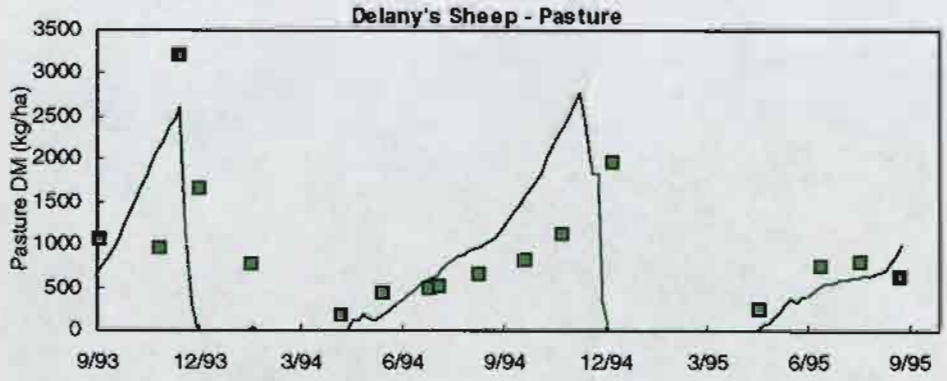

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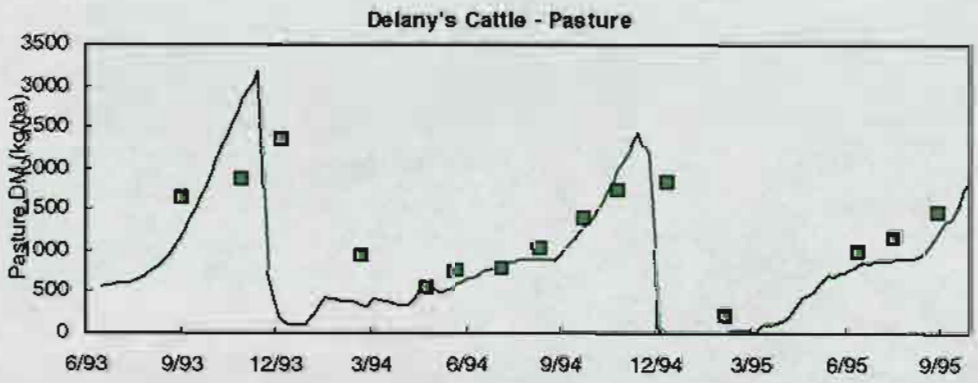

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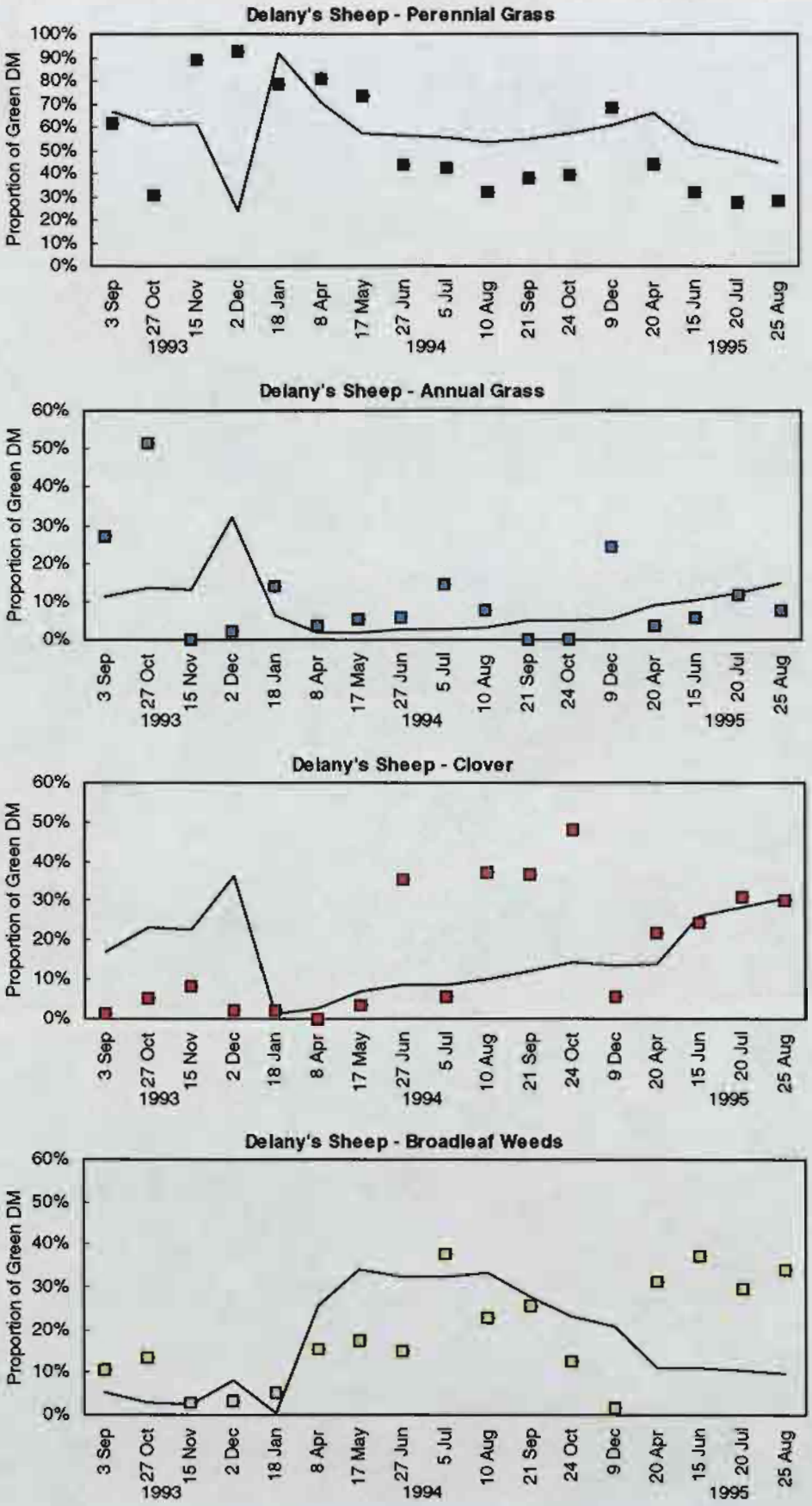


Figure 3.6. Simulation of pasture composition for the "continuously grazed" treatment of the Delany's cattle (Hamilton) grazing management site, using the GRAZPLAN pasture and animal models with the modifications reported in section 2. Symbols represent measured figures for each species' proportion of green dry matter (means of two replicates), with error bars showing confidence limits. Points on the black lines represent the predictions of the model at each measurement time.

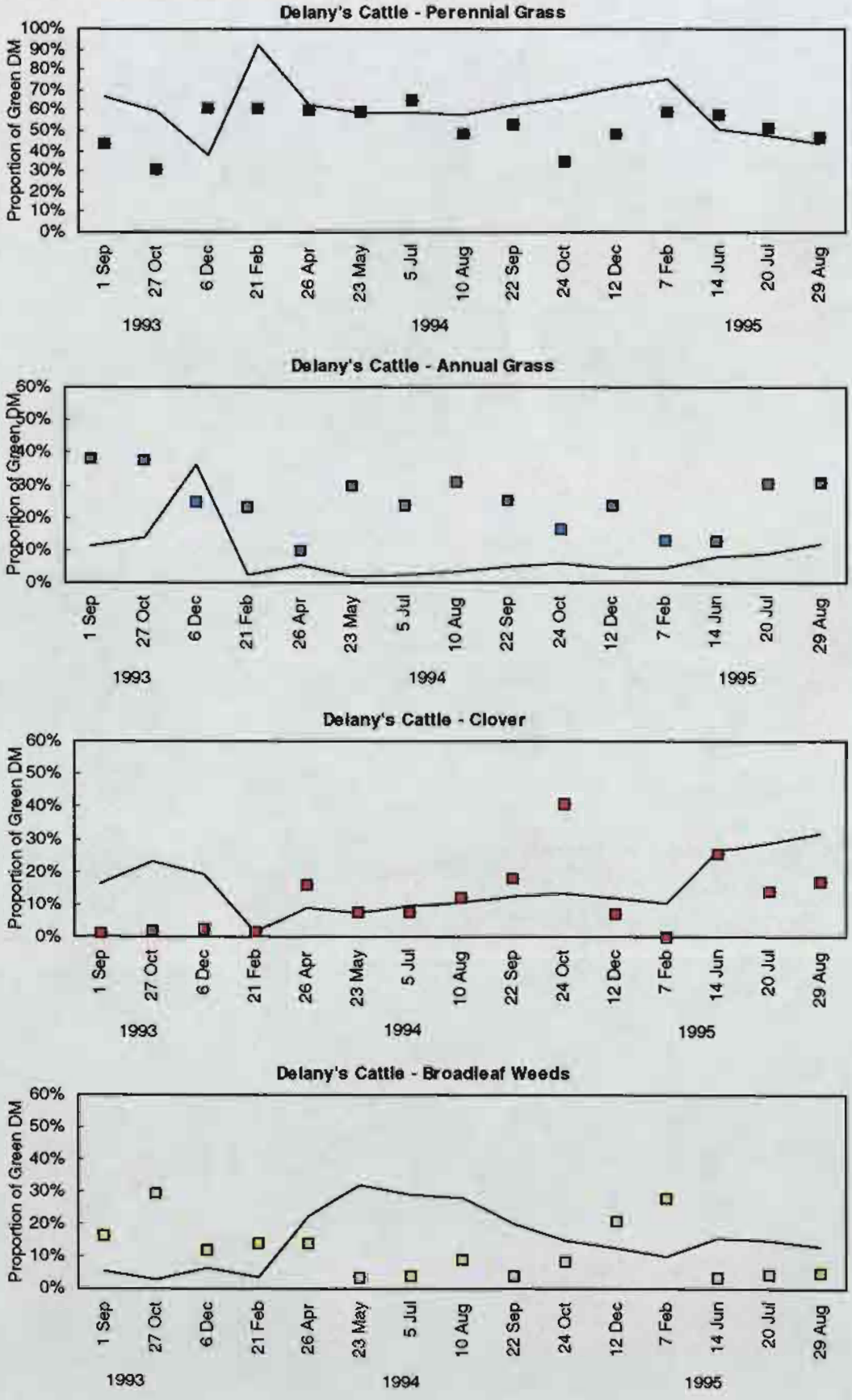


Figure 3.7. Simulation of pasture dry matter for four treatments of the Wallaroo 3 (Canberra) experiment, using the GRAZPLAN pasture, animal and nutrient cycling models with the modifications reported in section 2. Symbols represent measured figures for available green pasture (■) and total pasture mass (■), while the continuous lines of corresponding colours show the time course of the simulation.

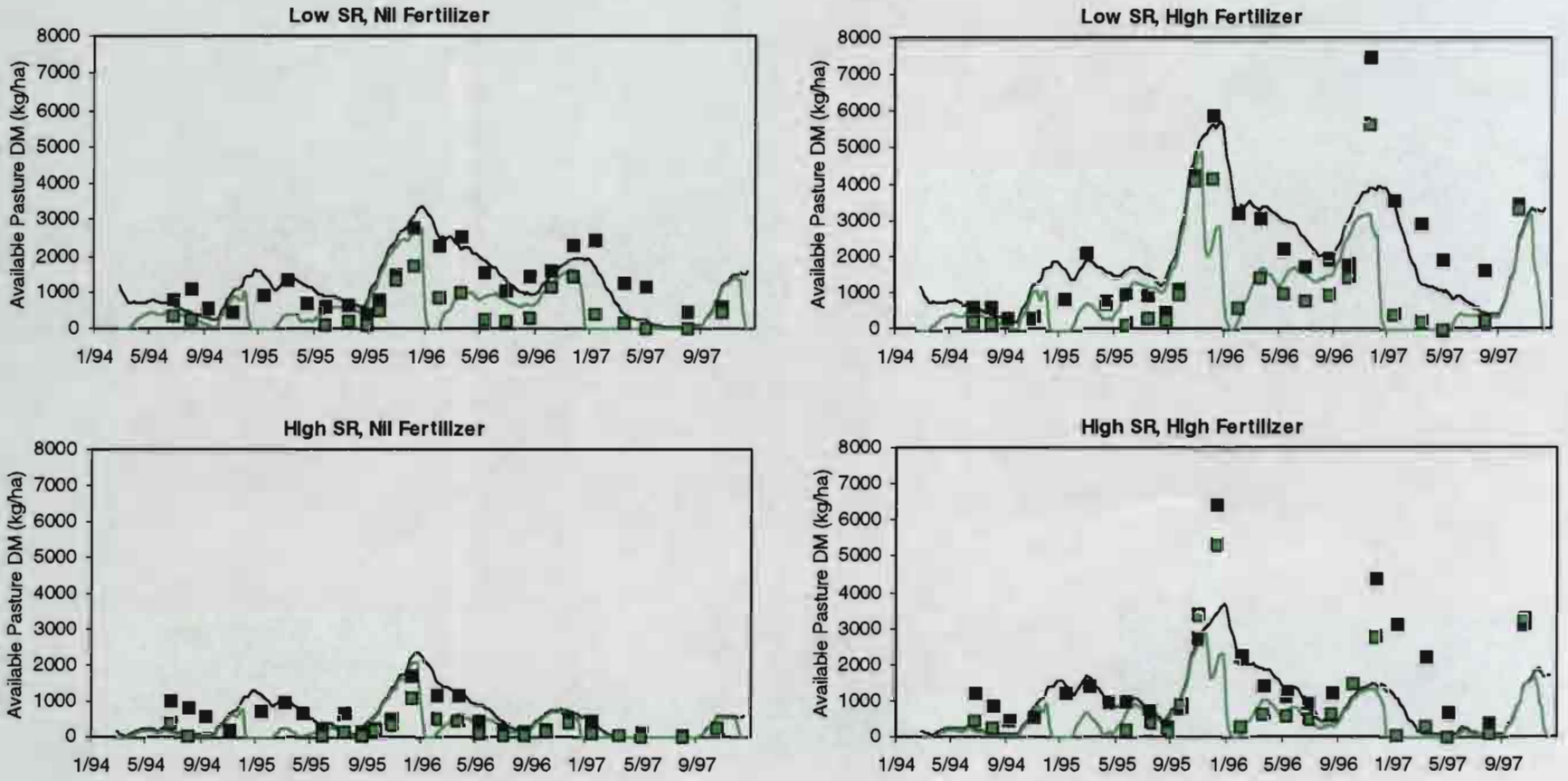
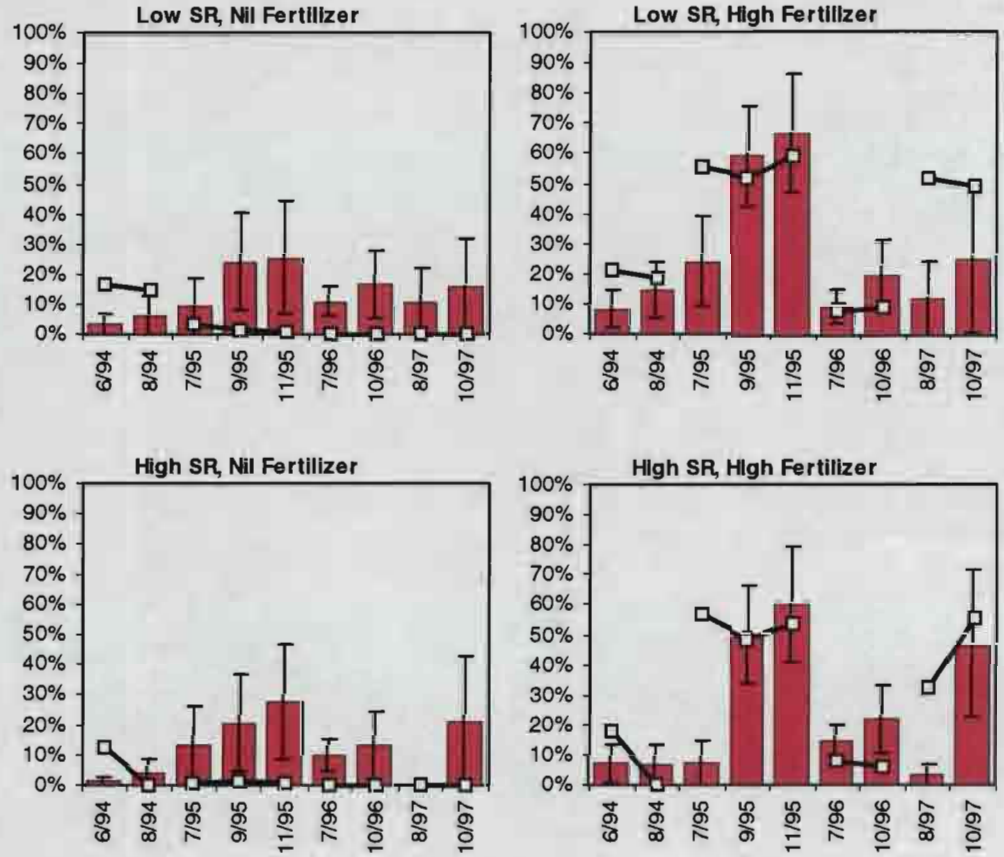
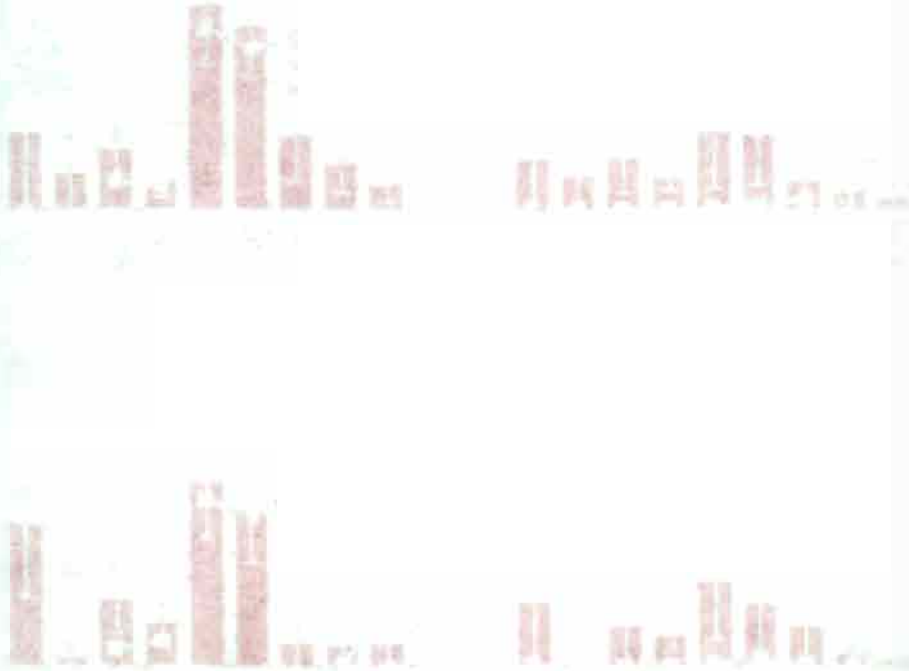


Figure 3.8. Simulation of clover content for for four treatments of the Wallaroo 3 (Canberra) experiment, using the GRAZPLAN pasture, animal and nutrient cycling models with the modifications reported in section 2. Bars represent measured figures for the proportion of clover in the green dry matter (means of three replicates), with error bars showing confidence limits. Points on the black lines represent the predictions of the model at each measurement time.





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