Using GIS and the GRAZPLAN Simulation Models to Assess the Effect of Climate Variability on Pasture Production

[1]Michael J. Hill, [1]Graham E. Donald, and [2]Andrew D. Moore
[1]CSIRO Division of Animal Production, CCMAR, Private Bag, PO. Wembley, WA, 6014, and [2]CSIRO Division of Plant Industry, c/- CRC for Soil & Land Management Hannaford Building Private Bag 2, Glen Osmond, SA, 5064.

Abstract In this study, the GRAZPLAN simulation models of pasture growth and animal production are used to assess the effect of climate variability on net primary production of herbage from a phalaris/clover-based pasture in the New England region of NSW, Australia. Simulations were run for the following data sets: the 21 year weather record for 1974–1994 from the CSIRO Research Station, "Chiswick"; five regional weather records created by classifying mean climate surfaces for an 80 x 90 km area ranging in elevation from 700–1400 m asl and using differences in class means to adjust the "Chiswick" record to create long term daily weather for each class; and regional weather records adjusted for different frequencies and intensities of rainfall within the same seasonal total. Variability in seasonal net primary production was mostly explained by current and previous season rainfall and a temperature factor, but was poorly predicted in autumn. Frequency, intensity and distribution of rainfall was an important secondary contributor to variability.

1. INTRODUCTION

Climate variability significantly affects pasture and animal production in eastern Australia. This is particularly so in northern NSW where rainfall is slightly summer dominant, but unreliably distributed throughout the year. The variability is significant in time frames ranging from years and seasons down to weeks and days. The effects are multiplied or diminished by the interaction between the time of year, the prior conditions and the responsiveness of the pasture. The variability is also expressed in space at scales ranging from paddocks to regions, and in response to topographic features. The response of pasture production to climate variability is of interest in the context of drought management, both economic and ecological sustainability, and future climate change. Simulation models provide the best means of analysing potential responses since experimental data are restricted in time and space. In this study the GRAZPLAN simulation models (Donnelly et al., 1997) are used to assess the effect of climate variability on phalaris/clover-based pasture on the Northern Tablelands of NSW, Australia.

2. METHODS

2.1 Regional Environment

The simulations were carried out for a region of 78.3 x 91.0 kilometres covering the southern half of the Northern Tablelands of NSW (centred on 30.5 °S 151.5 °E), Australia. The pastures are primarily based on native perennial grasses with introduced legumes such as white clover, naturalised legumes and grasses and some history of superphosphate application. Perhaps 10-15% of pastures are based on introduced perennial grasses, and a similar proportion may be unfertilised native perennial pasture used for fine wool production. Elevation was described by a 100 m spatial resolution digital elevation model (DEM).

2.2 Weather Data

A 21 year period between 1974–1994 from the long term weather record for the CSIRO Pastoral Research Laboratory "Chiswick" was used as the basis for the simulations. The period was chosen from the total record from 1959–1997 to provide an acceptable sample of historical variation whilst limiting the volume of input and output data to manageable proportions. These data provided a continuous daily record of all weather variables required for simulations using the GrassGro DSS. A continuous record of evaporation and radiation was not available for this period for other weather stations within the study region.

2.3 Climatic Zones

Variation in climate within the study region was described by interpolation and classification. Mean monthly climate surfaces were constructed from the DEM, the Australian Climate Surfaces and the ESOCLIM program (Hutchinson 1989) using elevation, latitude, longitude and distance from the coast as independent variables. Monthly surfaces for maximum and minimum temperature, rainfall and evaporation were subjected to polythetic divisive clustering (Hedges and Vickery, 1987) to classify climatic zones. The nominal 20 classes were aggregated on the basis of an appraisal of the two-dimensional ordination of class means, a dendrogram of the classification and the class bond strengths. Mean monthly averages for each zone were extracted from the climate surfaces and a table of differences between these values and the mean monthly averages for "Chiswick" was established. The table of

Table 1. Historical variability in climate data and simulated runoff for the 1974-1994 period at Chiswick.

Variable	Winter		Spring		Summer		Autumn	
	Mn	Sd.	Mn	Sd.	Mn	Sd.	Mn	Sd.
Total rain (mm)	132	51	185	67	278	91	158	90
Total evap (mm)	132	10	309	23	410	24	240	21
P:E ratio	1.00	0.38	0.61	0.24	0.69	0.25	0.66	0.40
Max. Temp.	12.6	1.1	19.5	1.8	25.7	1.5	19.8	1.2
Min. Temp.	1.0	1.4	6.3	0.9	12.6	1.0	7.6	1.5
Radiation	12.8	0.7	22.8	1.1	24.9	0.9	16.2	0.8
Longest dry period	20.4	7.0	15.4	6.0	15.0	4.8	23.1	12.8
No. of rain events	17.6	5.6	22.1	4.9	23.8	4.8	16.9	6.6
Max > 30 °C	0.0	0.0	1.1	2.1	11.8	6.8	1.0	1.7
Min < 3 °C	64.1	10.4	23.2	7.6	0.5	1.4	17.4	9.7
Median event day	39.4	8.3	48.2	5.8	41.7	7.2	45.1	14.1
Median rainfall day	42.0	15.3	53.8	11.1	47.3	15.1	44.3	22.2
Runoff (mm)	11.6	2.7	3.00	9.5	14.0	19.4	5.5	10.5

differences was used to adjust the weather record for "Chiswick" to create daily weather records for each zone.

The daily weather records for each zone provided adjustments in the magnitude of weather events, but with the same sequence and timing of events as experienced at the "Chiswick" site. Examination of historical means for Bundarra, just outside the western edge of the region in the warmest and driest zone, and Guyra, in the coolest and wettest zone, showed excellent agreement with the means for the adjusted climate sets. We recognise that small rainfall events are probably localised within this region and that application of the "Chiswick" sequence to other areas of the study region can only approximate the actual rainfall sequences at the geographical extremes. The relativities between temperature and moisture optima for pasture growth and seasonal temperature and moisture regimes change across zones.

2.4 Plant Response

The impact of climate on net primary production from phalaris-based pasture was described in terms of seasonal responses. This aggregation by season matches the phenological behaviour of this perennial grass which is relatively dormant in summer and early autumn, vegetative in autumn and early winter, and reproductive in late winter and spring. The association of reproductive growth with spring provides the greatest potential growth rate and therefore the greatest potential responsiveness to weather conditions. The seasonal aggregation also relates well to the climatic pattern of the environment where growth is severely limited by temperature in winter, and potentially limited by moisture in spring, summer and autumn.

Table 2. Correlations between weather variables and simulated seasonal NPP for the 1975-1995 period. Correlation coefficients greater than 0.42 are significant at $P < 0.05$ (bold). "Lag Temp" refers to the mean temperature in the preceding season.

Variable	Winter	Spring	Summer	Autumn
Total rain	**0.54**	**0.83**	**0.76**	0.17
Total evap	0.15	**-0.46**	-0.12	**-0.47**
P:E ratio	**0.50**	**0.82**	**0.70**	0.23
Max. Temp.	0.41	**-0.72**	**-0.76**	**-0.57**
Min. Temp.	**0.81**	-0.28	**-0.54**	-0.27
Lag Temp.	**0.54**	0.00	**-0.43**	**-0.50**
Radiation	-0.41	**-0.76**	**-0.58**	-0.38
Longest dry period	0.07	**-0.58**	-0.34	-0.43
No. of rain events	**0.60**	**0.70**	**0.69**	0.18
Max > 30 °C	N/A	**-0.49**	**-0.65**	-0.30
Min < 3 °C	**-0.81**	0.12	-0.00	**0.47**
Median event day	0.16	0.11	0.19	-0.15
Median rainfall day	0.18	0.33	0.13	-0.34
Lag Rain	0.20	**0.53**	**0.62**	**0.70**

2.5 Perturbation of Weather Data

The weather data sets were perturbed to induce extra climatic variability. Global warming scenarios predict increased variability in weather events through changes in frequency and amplitude. We hypothesised that changes in rainfall frequency and intensity might significantly affect net primary production (NPP; kg/ha dry matter) from pastures. In order to test this, the number and intensity of rainfall events within a season was modified by adding event 1 to event 2 (a), adding events 1 and 2 to event 3 (b), adding events 1, 2 and 3 to event 4 (c), and adding events 1, 2, 3 and 4 to event 5 (d). This had the effect of reducing the frequency and increasing the intensity of events, and shifting the date of median rainfall later in the season - designated as "lumping" from here on. By this means, we sought to examine the influence of frequency and intensity of rainfall without changing the seasonal total.

2.6 Simulations

The model (Moore et al., 1997) was initially developed for improved perennial grass-based pastures and is best validated for these pastures. Hence we chose to run the simulations for a phalaris/clover-based pasture in the Northern Tablelands environment using a well established parameter set; parameter sets for white clover and some annual species are under development. The weather data sets were created with FORTRAN routines. Simulations were run for the years 1972-1994 allowing two years for the model to stabilise. The following simulations were run: the "Chiswick" data for the historical record, and frequency/intensity adjustments to define correlations

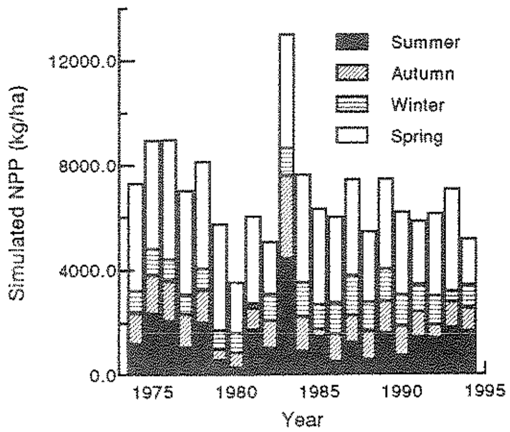

Figure 1. Seasonal and annual simulated NPP for the 21 year period from 1974-1994.

between seasonal weather and NPP; each of the five climate regions to define the base spatial variation; and four frequency/intensity changes x five climate regions. Output data were aggregated by season, imported into a spreadsheet for formatting, and transferred to the JMP statistical package for analysis.

3. RESULTS AND DISCUSSION

3.1 Historical data

The general pattern of climatic variability for the Chiswick site is shown in Table 1. Rainfall is summer dominant, evaporation exceeds rainfall in spring, summer and autumn and low temperatures limit growth in winter. Simulated seasonal NPP is greatest in spring, but variability in simulated NPP is greatest in summer and autumn (Figure 1). NPP estimates are a little lower than experimental measurements since a moderate fertility setting was used in the model. Correlations between weather variables and simulated seasonal NPP (Table 2) show that NPP is least responsive to moisture variables in autumn, and most responsive in spring and summer. Correlation coefficients with temperature variables are positive in winter and negative in the other seasons. Autumn NPP is strongly influenced by temperature and rainfall in the preceding summer. Correlations between seasonal NPP and variables describing the timing of rainfall within the season were not significant. In spring, the wettest years 1980 and 1994 were relatively warm, but the driest years spanned the whole temperature range (Figure 2). In summer, two very wet seasons had low maximum temperatures. There was no significant relationship between rainfall and temperature in either season (Figure 2). Figure 3 depicts the relationships between simulated NPP and seasonal rainfall and maximum temperature. There is no trend in the dataspaces for autumn and winter. The outlying point in winter is for 1983 and appears to be the result of early breaking of dormancy and growth initiation in the model due to high autumn rainfall and low autumn temperatures. Seasonal NPP for spring and

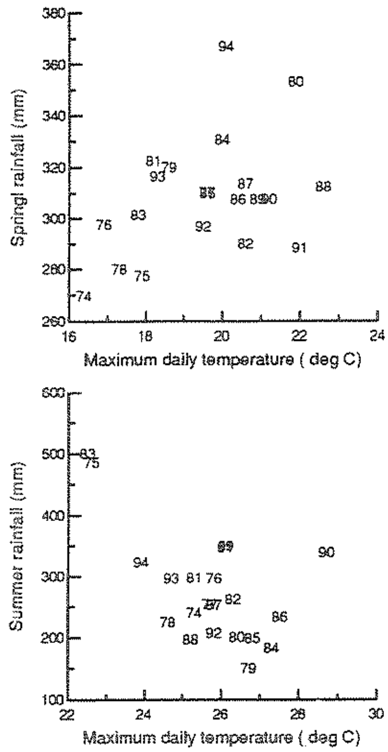

Figure 2. Rainfall/maximum temperature dataspaces for spring and summer.

summer have similar slopes but different intercepts in the rainfall dataspace, but a single line with a negative slope can be fitted to the combined spring and summer data in the maximum temperature dataspace. The results illustrate the effect of different potential growth rates associated with vegetative (autumn- winter) and reproductive (spring-summer) phases of plant growth, and the impact of temperature and moisture-induced dormancy (summer-autumn). The responses shown reflect the thresholds and relationships used to drive growth in the model.

3.2 Changing the frequency and intensity of rainfall

Since spring is the most responsive time for plant growth, the effects of changing the frequency and intensity of rainfall are examined for the spring season. Years were divided into < 33 percentile, 33–67 percentile and >67 percentile rainfalls from the full 1959–1995 historical record. Lumping the within-season rainfall had a large beneficial effect on NPP for <33 percentile years (Figure 4). This was particularly so for 1988 which was very warm in spring (Figure 2); the benefit here being a significant increase in the effectiveness of rainfall at relatively good seasonal levels in a period of high potential water use. The effect of lumping was relatively small for >67 percentile years (Figure 4) when moisture was mostly non-limiting. The lumping procedure increased the seasonal day number of the median rainfall amount; but the only large change occurred for 1991 where the day number was moved from 56 to 78 (Figure 5). It is notable that day of median rainfall amount (Figure 5) was very early in the season in 1988, the year which shows the greatest response to lumping.

Table 3. Mean and standard deviation for number of days when simulated soil moisture was below the 0.35 threshold for historical data, and data where four of every five rainfall events were removed and added to the fifth.

Rainfall percentile	Summer	Autumn	Winter	Spring
		Historical data		
<33	31.8 ± 14.3	53.5 ± 11.4	25.0 ± 29.5	47.8 ± 15.6
33-67	26.9 ± 9.2	24.3 ± 22.9	5.0 ± 7.8	18.4 ± 12.4
>67	12.8 ± 8.1	21.3 ± 15.3	6.6 ± 10.8	3.7 ± 5.7
		1234 added to 5		
<33	26.0 ± 9.0	31.2 ± 20.5	17.3 ± 25.7	38.1 ± 16.8
33-67	22.0 ± 12.4	16.3 ± 24.4	2.2 ± 4.0	10.1 ±10.1
>67	8.8 ± 4.6	14.0 ± 17.2	5.6 ± 9.3	2.3 ± 4.1

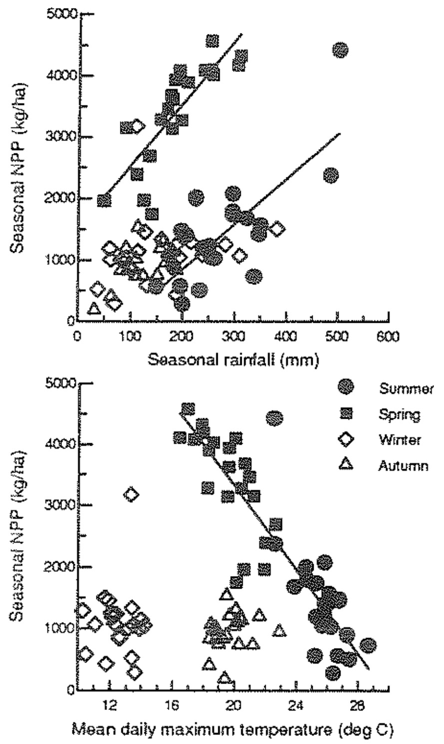

Figure 3. Response to rainfall and maximum temperature of simulated seasonal NPP. The regression equations are:
spring NPP = 1515 + 10.2 (Rain) $R^2 = 0.68$
summer NPP = -625 + 7.75 (Rain) $R^2 = 0.57$
spring/summer NPP = 10068.9 - 338.7 (MaxT) $R^2 = 0.80$

Therefore the NPP increases observed were mostly due to increased rainfall effectiveness. The lumping changes the dynamics of water use in the model, with any event becoming more likely to move water to a depth where it will be transpired rather than lost through soil evaporation. This decreases the number of days when moisture is below the growth threshold. The GrassGro DSS uses thresholds to define the plant growth limits. Soil moisture begins to limit growth when the proportion of the average of available soil moisture falls below 0.35 [Moore et al., 1997]. The impact of changing the frequency and intensity of rainfall is

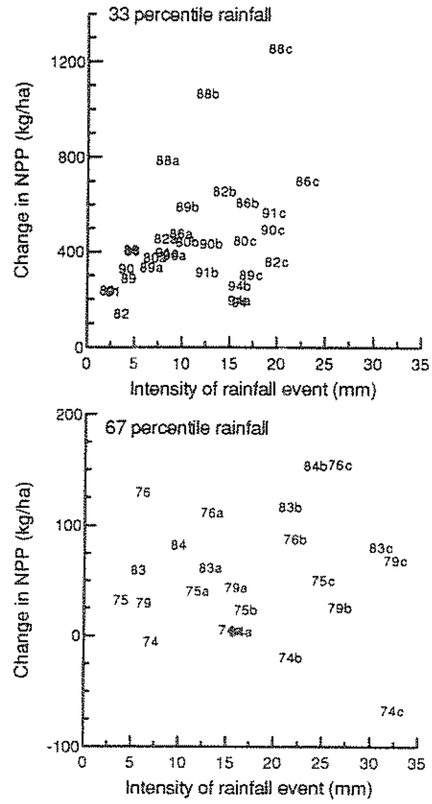

Figure 4. Change in NPP with intensity of rainfall events in spring for years below the 33 percentile, and above the 67 percentile. Letters next to year symbols indicate level of modification to frequency and intensity.

illustrated by the number days in a season when soil moisture was below the 0.35 threshold (Table 3). The average number of days below the 0.35 threshold is reduced in all seasons by removing four of every five rainfall events and adding them to the fifth. This response for the most extreme lumping reflects the trend for the other less extreme lumping procedures. While the averages always reduced with lumping, there were sometimes increases as a result of lumping due to the particular distribution and intensity of rainfall in individual years.

3.3 Variation in Response over Climate Zones

The zones are summarised by increasing mean elevation from zone 1 to zone 5 (Table 4); temperatures decrease correspondingly (data not given). Summer, autumn and winter rainfall tend to increase from zone 1 to zone 5, but spring rainfall is fairly constant (data not given). There is an increase in summer NPP from zone 1 to zone 5 as temperatures decrease and rainfall effectiveness increases. Year to year variability of the spring season reduces with increasing elevation since probability of moisture stress declines. Year to year variability of the summer season is greatest at the lowest elevation where the potential is greatest for dry conditions resulting in no growth. However,

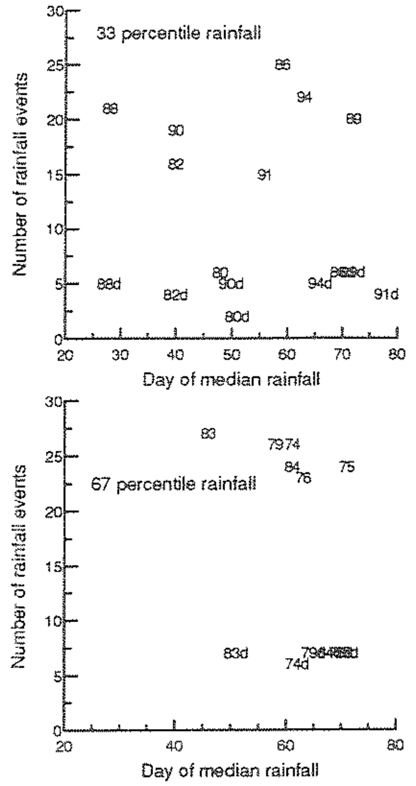

Figure 5. Change in day of median spring rainfall amount between historical data and the highest level of frequency and intensity modification for years below the 33 percentile and years above the 67 percentile

year to year variability of autumn and winter seasons is greatest at high elevation. Winters may be so cold that no growth is possible, regional droughts still occur, but mild summers may lead to early autumn growth. Where frequency and intensity were perturbed over the five climate zones, spring NPP was increased and the year to year variability was reduced by "lumping" (Table 5). There was no interaction between "lumping" and zones.

3.4 Factors Controlling Variability

Multiple regressions on weather variables and simulated seasonal NPP for Chiswick (Table 5) showed that much of the variation in winter and spring could be explained by previous and current season rainfall, and temperature terms. However, the timing and intensity of rainfall, and a measure of coolness made a significant contribution to variation in summer. Autumn responses were poorly predicted. In multiple regressions with the Chiswick data perturbed for frequency and intensity (data not given), number of events was a significant term in spring, summer and winter; day of median rainfall was significant in winter and spring; and day of median event number was significant in summer and autumn. Thus some of the variability not explained by the major temperature and rainfall factors was explained by the rainfall timing and

Table 4 Mean simulated seasonal NPP and temporal CV of NPP for the 1974-1994 period over five climatic regions; and spring simulated NPP after four of every five rainfall events was added to the fifth. Zones are characterised by mean and CV of elevation.

Region	Elev-ation	Summer	Autumn	Winter	Spring	Spring 1-4>5
			NPP (kg/ha)			
1	721	502	730	973	2633	3006
2	846	695	823	898	2928	3304
3	970	969	927	877	3120	3490
4	1070	1136	994	956	3203	3587
5	1242	1566	1295	761	3285	3605
			CV%			
1	6.9	84	36	29	34	29
2	5.5	68	36	32	30	25
3	4.8	62	34	35	28	23
4	4.2	55	34	32	27	22
5	5.7	61	60	42	21	19

Table 5. Factors controlling variability in seasonal NPP for the Chiswick historical weather data. Numerals denote the order of importance for each season, with 1 the most significant term in the multiple regression.

Factors included in regression ($P<0.05$)	Summer	Autumn	Winter	Spring
6 month rainfall	4	1	3	1
Minimum T	1		1	
Maximum T		2	2	3
Median event day	2			
Longest dry period				2
Days < 3 °C	3			
Days > 30 °C		3		
No. of rain events	5			
Median rainfall day	6			
R^2	0.87	0.53	0.86	0.83

Table 6. Factors contributing to variability in spring NPP across zones with "lumping" of rainfall events. Numerals denote the order of importance for each season, with 1 the most significant term in the multiple regression.

Factors included in regression ($P<0.05$)	Zone 1	2	3	4	5
6 month rainfall	1	1	1	1	1
Seasonal rainfall	5	2	2	2	
No. of rain events	3	6	6	3	7
Median rainfall day	2			7	4
Evaporation		3	3	5	5
Lagged rainfall					2
Lagged mean T					3
P/E ratio		4	4	4	6
Minimum T	4	7	7		
Days < 3 °C		5	5		
Maximum T				6	
Radiation					8
R^2	0.91	0.92	0.90	0.84	0.78

intensity factors (Figures 4 and 5). Multiple regressions on spring NPP for all data perturbed for frequency and intensity using zones as sets (Table 6) showed that the intercepts were all significantly different ($F=2.79$; $P<0.001$), but the slopes for zones 2, 3 and 4 were the same ($F=1.24$; ns) while the slopes for 1, 2-4 and 5 were significantly different ($F=2.43$; $P<0.001$). The percentage of variation explained by 6 month rainfall declined from > 80% in zone 1 to 56% in zone 5. Less variation was explained by the regressions as mean altitude increased from zone 1 to zone 5. The rainfall and temperature conditions in winter were important sources of variation in spring NPP in zone 5.

4. CONCLUSIONS

Total rainfall for the current and previous season and a temperature measure were the most important predictors of variation in simulated seasonal NPP, although variation was poorly predicted in autumn. The number, intensity and timing of rainfall events were important secondary sources of variation in spring when potential production is highest. Unexplained variation in NPP was greatest for spring at high elevation and for summer at low elevation. The model appeared to provide a highly sensitive means of examining climate variability, although sensitivity in autumn may be dependent on the dormancy parameters. A more complete coverage of the impact of climate variability on NPP from these pastures would be obtained when reliable parameter sets for native grasses and white clover are available, as these may significantly change the relationships in summer and autumn.

5. ACKNOWLEDGEMENTS

This research was conducted as part of the Climate Variability Multi-Divisional Program within CSIRO. CSIRO Division of Animal Production is partially funded by Australian wool growers through the International Wool Secretariat.

6. REFERENCES

CSIRO, Climate change scenarios for the Australian region. Climate Impact Group, CSIRO Division of Atmospheric Research, 8 pp, 1996.

Donnelly, J. R., Moore, A. D. and Freer, M., GRAZPLAN: Decision support systems for Australian grazing enterprises. I. Overview of the GRAZPLAN project, and a description of the MetAccess and LambAlive DSS. *Agric. Sys. 54*, 57-76, 1997.

Hedges, D.A. and Vickery, P.J., Use of a principal components strategy as the basis for an unsupervised classification routine to examine Landsat data from grassland vegetation. Proceedings of the 4th Australasian Remote Sensing Conference 1, 178-88, 1987.

Hutchinson, M. F., A new objective method for spatial interpolation of meteorological variables from irregular networks applied to the estimation of monthly mean solar radiation, temperature, precipitation and windrun. CSIRO, Australia, Div. Wat. Res. Tech. Memor. 89/5, 95-104. 1989.

Moore, A. D., Donnelly, J. R. and Freer, M., GRAZPLAN: Decision support systems for Australian grazing enterprises. III. Pasture growth and soil moisture submodels and the GrassGro DSS. *Agric. Sys.* (in press), 1997.