Simulation of grazing strategies for beef production in north-eastern Queensland

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1. Abstract

A simulation study was conducted to compare different grazing strategies for steers grazing open woodlands in north-eastern Queensland. Simulations were carried out for a wide range of possible stocking rates and utilisation levels using 107 years of daily climate for Charters Towers (1889-1996). Strategies were compared in terms of steer liveweight gain (LWG) per ha, risk of weight loss, pasture availability, frequency of burning and soil loss.

This paper describes work in progress and hence strong caveats are placed on the ranking of strategies simulated here. Several important feedbacks of overgrazing have not yet been included in the model: the effect of soil loss on physical and biological attributes such as potential infiltration, available water range and potential nutrient uptake; the effect of frequency of pasture burning on woody weeds and regrowth; and the effect of drought on nutrient availability. Future work will concentrate on modelling feedbacks of changes in resource condition on cattle production. An annual LWG model was developed as a function of utilisation and number of days a simulated plant growth index (0-1) exceeded a threshold (0.05). The development of a monthly LWG model is a high priority to allow more flexible within-year stocking rate strategies to be evaluated.

The stocking rate strategies and the best LWG/ha averaged over the 107 years were:

1) *constant* stocking rate: 20.3kg LWG/ha/yr;
2) stocking rate changed in June each year to eat a constant proportion of the standing dry matter in June (*reactive* strategy): 24.3 kg LWG/ha/yr;
3) stocking rate changed each year in June to consume a constant proportion of the future year's growth (*perfect knowledge* strategy): 29.2 kg LWG/ha/yr;
4) stocking rate changed in November each year to eat a constant proportion of forecast growth based on August-October SOI (*SOI-forecast* strategy): 22.4 kg LWG/ha/yr; and
5) stocking rate changed in June each year (as in 2) but base on forecast growth assuming an increase in SOI forecasting skill lead-time (*increased SOI forecast lead-time* strategy): 25.2 kg LWG/ha/yr.

For LWG/ha, the advantage of the best flexible strategies (2-5) over the best constant stocking rate were 20, 44, 10 and 24% respectively.

For strategies achieving an average LWG/hd of 100 kg/yr, the simulation studies indicated that varying the *reactive* stocking rate strategy in June with a forecast of the next year's pasture growth would increase LWG/ha by 9% (25.2/23.1), would reduce the risk of liveweight loss by 57% (from -3.9 to -1.7 kg/hd), would reduce risk of low pasture yield, but would increase the risk of soil loss (4%). Alternative strategies could also be developed (e.g. 50% reduced stocking rate in El Niño years only) which could reduce soil loss by 7% (955/1022) without reducing production (LWG/ha).

When strategies 1 to 5 were compared at the same average stocking rate over the 107 years the results were: *constant* 20.2, *reactive* 20.7, *SOI-forecast* 21.3, *increased SOI forecast lead-time* 23.0, and *perfect knowledge* 24.7 kg LWG/ha. The preferred strategy of *increased SOI forecast lead-time* not only increased production by 15% but had the lowest soil loss of the above strategies. These studies highlight the value of achieving in June the current skill of seasonal forecasting which is now available in November.

2. Introduction

Year-to-year variation in rainfall is a major problem for beef enterprises in the semi-arid tropics of N.E. Queensland (Scanlan *et al.* 1994). For example, from 1964 to 1989 Dalrymple Shire has been drought declared 12 times with a frequency of declaration of 1 in 2.2 years and total time declared of 34% (Daly 1994). Charters Towers annual (July to June) rainfall variability is high, e.g. co-efficient of variation of 40 % for 1883 to 1992. One cause of climatic variability in this region is the effect of the El Niño/Southern Oscillation (ENSO) phenomenon on rainfall as shown by the relatively high correlation in the last 30 years between spring Southern Oscillation Index (SOI) and subsequent summer (November to March) rainfall (r^2=0.25, McKeon *et al.* 1990).

Decade-to-decade and generation-to-generation variations in rainfall are also high (Lough 1991). Reconstruction of Burdekin river flow suggested that both drier and wetter decades and 30 year periods had occurred before the current century. The grazing management decisions which are made against this background of climatic uncertainty include stocking rate, frequency of burning, control of woody weeds, use of animal supplements and herd management. Of these decisions, stocking rate or the management of grazing pressure has a major impact on resource management (Gardener *et al.* 1990, De Corte *et al.* 1991). Stocking rate affects pasture yield not only through the processes of consumption and trampling, but also through the effects of grazing on pasture composition (McIvor *et al.* 1995a). Increased grazing pressure can result in less pasture yield, less pasture growth, increased run-off and soil loss (Scanlan *et al.* 1996a), reduced burning opportunities and increased risk of woody weed growth (Burrows *et al.* 1990).

Many possible strategies (Stafford Smith 1992) are available to manage grazing pressure including:

1) constant year-to-year stocking rate;
2) stocking rate adjusted each year to eat of a constant proportion of existing pasture yield; and
3) stocking rates adjusted each year to eat a constant proportion of expected future or forecast pasture growth.

Graziers use some of these options (Scanlan *et al.* 1994) but no data are available to formally compare the effects of these options on production and resource status. Not only are different strategies available but the optimal level of pasture utilisation is also uncertain judging by the large variation in pasture utilisation between properties (Scanlan *et al.* 1994). In eastern Queensland, historical grazing trials with beef cattle have concentrated on comparing only varying levels of constant stocking rate. Grazing trials comparing different stocking rate ‘decision rules’ have only just commenced (e.g. Smith 1996). Simulation modelling provides one approach to extrapolate existing research findings and producer experience to formally compare a wide range of grazing strategies over a wider range of climatic conditions (using historical climate data) than can be experienced in a typical field trial (White 1978, McKeon *et al.* 1990). This working paper describes the modification of a simulation model (GRASP) to evaluate grazing strategies on steer growth and risk of resource damage. Recommendation are also made for future developments required to better evaluate seasonal forecasts.

There is possible confusion about the appropriate use of the words ‘strategy’ and ‘tactics’ in grazing management. ‘Strategies’ are concerned with longer time frames than ‘tactics’, e.g. strategies used in wars compared to tactics used in battle. In these simulation studies we are evaluating long term strategies involving annual stocking rate decisions. When compared to the constant stocking rate strategy, varying stocking rates each year based on a rule could be described as ‘tactical’ because each year is treated as a separate decision. However, we prefer the term ‘strategy’ here as we are comparing decision rules to vary stocking rate each year based on information available at the time. These ‘varying stocking rate strategies’ represent rational approaches to deal with the full spectrum of rainfall variability. They are not really ‘tactical’ when compared to real world decisions which involve response to short term (monthly to seasonal) fluctuations in markets, rainfall, government regulations etc. In this paper, we evaluate different decision rules as if they were inflexible recipes. Scanlan *et al.* (1994) found in a study of 45 properties over three years that herd numbers were reported to change by ± ~90% and hence no constraints on stocking rate have been placed on the simulation studies reported here. Working Paper 9 (Stafford Smith *et al.* 1997) examines the impact of commercial constraints on the implementation of these decision rules by simulating a breeder-steer finishing enterprise.

Appreciation of seasonal rainfall forecasting based on ENSO has improved greatly in the last 20 years (McKeon and White 1992). Since Gibbs and Maher (1967) detailed the impact of drought on agriculture and grazing, various forecasting systems suitable for use in land management have been developed based on the sound understanding of climatic mechanisms and the uncertainties attached to the use of imperfect forecasts (Pittock 1975, Nicholls 1983, Allan 1988, Clewett *et al.* 1988, McKeon *et al.*, 1990, Stone and Auliciems 1992, Hammer *et al.* 1990, Stone and McKeon 1992, Stone *et al.* 1996).

In this study we only examine the lagged SOI system of Clewett *et al.* (1988) and the theoretical potential of current climate models under development, e.g. NOAA (1996). Future studies will examine the use of the SOI phase system (Stone and Auliciems 1992) and the Sea Surface Temperature prediction models of Hunt (1991), Hunt *et al.* (1994), Smith (1994), Kleeman *et al.* (1995) and Hunt and Davies (1997).

Some authors have examined the correlations between rainfall variation and solar activity (e.g. Noble and Vines 1993). Recent climate modelling studies (Robock 1996, Haig 1996) support possible mechanistic understanding for these controversial correlations. In future studies we will also evaluate the potential of these less ‘politically correct’ forecasts.

3. Word model of processes in soil-pasture-animal system

A brief description will now be provided of the major processes in the grazing system and those relationships in the model which simulate the system.

The semi-arid tropical grazing lands, when in good condition, are mainly an open woodland with an understory of perennial tussock grasses, growing on a wide variety of soils of low slopes (2-3%). The major hydrological and erosion processes are:

1) run-off which is a function of surface cover, rainfall intensity and soil-water deficit (Scanlan *et al.* 1996a);

2) evapotranspiration made up of soil evaporation, grass transpiration and tree transpiration;
3) through drainage (Rickert and McKeon 1982, Scanlan and McKeon 1993); and
4) soil loss which is a function of cover, run-off and slope (McIvor *et al.* 1995b, Scanlan and McIvor 1993).

Standing pasture yield is the net result of the processes of pasture growth, death, detachment, consumption and trampling (McKeon *et al.* 1982, McKeon *et al.* 1990). Pasture growth in this summer rainfall environment is either limited by moisture or soil fertility, primarily nitrogen (McCown 1973, McCown *et al.* 1974, Mott *et al.* 1985). Potential perennial pasture growth when green cover or light interception is low is proportional to grass basal area (McKeon *et al.* 1990). Steer liveweight gain (LWG) is a function of length of growing season and pasture utilisation, i.e. the proportion of growth which has been eaten (McCown 1980-81, McKeon and Rickert 1984, McIvor and Monypenny 1995). Pasture burning increases potential LWG by about 15 kg/hd/yr (Ash *et al.* 1982). Intake restrictions are likely to occur when pasture yield is below 300 kg DM/ha (Ash *et al.* 1982). One of us (A. Ash) has observed that cattle with high *Bos indicus* content are able to graze to even lower yields without obvious reduction on intake.

Increased grazing pressure has several effects on pasture production:

1) grass basal area is reduced by grazing effects on plant death and the reduction of basal area of surviving plants especially during periods of drought (Scattini 1973, D.M. Orr pers. comm.);
2) feedback effects of defoliation on current growth through loss of photosynthetic area;
3) pasture composition (e.g. percentage perennials) is affected by heavy grazing of live tissue resulting in loss of perennial species and replacement by annuals with less production (McIvor *et al.* 1995a, D. Cooksley unpublished data);
4) increased pasture utilisation increases run-off through reduced surface cover (McIvor *et al.* 1995b) and fewer preferred infiltration sites such as areas occupied by perennial tussocks (K. Day pers. comm.) resulting in less water available for plant use (McCown *et al.* 1974);
5) increased soil loss reduces nutrients available for plant growth, infiltration and available water range (Williams and Charters 1991); and
6) reduced pasture yields result in fewer fires and increased opportunities for woody weed regrowth and possible increased growth of trees (Burrows *et al.* 1990, Burrows 1995).

In the following model development, we have addressed some of these feedbacks (1 to 5). However, a dynamic model of woody plant growth has not yet been fully developed (Scanlan and McKeon 1990) and hence only the risk of not being able to burn and thus control woody plant increase can be assessed. The possible role of heavy grazing in reducing woody plant regrowth (Scanlan *et al.* 1996b) also contributes to the uncertainty of correctly simulating the impact of grazing on the dynamics of woody plant growth.

3.1 GRASP computer model: brief description

GRASP is a deterministic, point-based model of soil-water, grass growth and animal production (sheep and cattle), developed and validated on tropical grasslands (McKeon *et al.* 1990, Day *et al.* 1993, Day *et al.* 1997). A full description of equations and assumptions in the pasture model is described in Littleboy and McKeon (1997). The model has been calibrated for over 40 pasture communities in Queensland. From daily inputs of rainfall, temperature, humidity, pan evaporation and solar radiation, soil-water is simulated for given soil attributes (texture and depth). Plant growth is calculated from transpiration, but includes the effects of vapour pressure deficit, temperature, radiation interception, nitrogen availability and grass basal area. The effect of variable tree density is simulated via the effects of trees on water use and nitrogen uptake. Animal production responses are calculated by multiple regression equations for live weight change (and wool growth for sheep) as a function of utilisation and length of growing season. These equations have been developed from grazing trials.

The soil-water model in GRASP is a simple one-dimensional multi-layered tipping bucket model. Infiltration occurs from layer to layer only when the water content of each layer has reached a user-defined field capacity. Four layers are simulated (0-10cm, 10-50cm, 50-100cm and 100cm down to an estimate of the bottom of the profile). Soil water in the lowest layer (>100cm) is available only for tree transpiration. Before infiltration, run-off is calculated as a function of cover, rainfall intensity and soil-water deficit using an equation derived from measured run-off data (Scanlan *et al.* 1996a). Deep drainage is also calculated although this component of the soil-water budget is yet to be validated and hence run-off could be underestimated under conditions where deep drainage is simulated.

From the point of view of this analysis, the most important hydrological processes are: (1) run-off due to low surface cover; (2) soil evaporation simulated for the 0-10 cm and 10-50 cm soil layers as a function of soil type and surface cover; and (3) transpiration from grass and trees. Tree density was assumed to be constant in the simulations reported here. Transpiration from grass is calculated from green cover, soil-water availability and Class A pan (or estimates where recorded data were not available). Green cover is recalculated each day from the simulated green biomass pool, itself the net result of gain by simulated growth and loss by animal intake and death due to aging, frost or soil-water deficit. Thus the simulations of soil-water and plant growth respond dynamically to the interaction of daily climate inputs (rainfall, pan evaporation, temperature, solar radiation and vapour pressure deficit) and management (stocking rate, fire, tree densities).

The feedbacks of heavy grazing pressure on plant production are simulated through the effects of run-off, perennial grass basal area, sensitivity to soil-water deficit and nitrogen uptake. Additionally changes in pasture composition (expressed as percentage perennials) gradually cause a shift in parameter values between those appropriate for perennial-dominated pastures and those dominated by annuals. As yet, no feedbacks of soil loss on nutrient availability or infiltration characteristics have been modelled. Effectively, GRASP allows the simulation of the risks of production losses but not the long-term consequences of taking some of those risks. It thus provides a framework for estimating animal production and pasture sustainability as a result of different sequences of climate and stocking strategies.

4. GRASP Model Calibration and further development

GRASP has a large number (>100) of parameters such as wilting point, field capacity and potential nitrogen uptake which can be estimated from field data. In this study, the model was parameterised using a number of exclosures and grazing trials from northern Australia (Day *et al.* 1997). We have assembled a composite parameter set using the best representation of each physical and biological process relevant to the northern black speargrass zone. Our aim was to examine the relative effects of grazing strategies for this region rather than at a particular site where there is likely to be insufficient information to parameterise all processes.

4.1 Soil water and pasture growth

The GRASP model has been calibrated for a wide range of exclosure sites or defoliation trials in northern Australia and provides a 'reasonable' simulation of within-season soil-water and plant yield (Figure 1). When parameterised with values which are measured on site (tree density, available water range, maximum nitrogen uptake, minimum nitrogen content of biomass and grass basal area) the model accounts for 60-70% of year-to-year variation in pasture yield (Figure 2) with greatest accuracy obtained in drought years. The empirical run-off model of Scanlan *et al.* (1996a) has also been independently tested by Yee Yet *et al.* (1994) although the use of more general approaches (curve numbers) would allow greater confidence in extrapolation across locations.

4.2 Simulation of pasture yield under grazing

A major grazing trial was conducted at Kangaroo Hills from 1964 to 1975 by CSIRO (Gillard 1979). A black speargrass community was oversown with the naturalised legume Townsville stylo. The eight treatments were:

0.21 steers/ha	X	tree killed	X	super phosphate
0.42 steers/ha		trees not killed		no super phosphate

The application of super phosphate had little effect, hence only four treatments are simulated here with the observed values being averaged across the phosphorus treatments. Townsville stylo remained a small component of pasture yield; up to 240 kg DM/ha where trees were not killed and up to 600 kg DM/ha where trees were killed. Hence the pasture and animal production values measured in the trial are relevant to native pastures although there was a possible variable contribution of legume production to animal nutrition and nitrogen cycling in pastures.

GRASP was parameterised for Kangaroo Hills by:

1) assuming a deep soil profile for all treatments. At present, data are not available to simulate characteristics of individual paddocks although this will be attempted in future studies;
2) pasture growth parameters, potential regrowth and grass transpiration efficiency were derived from pasture yields measured following an accidental burn (season of 1974-75) and from other exclosure data (Day *et al.* 1997);
3) potential nitrogen uptake was derived from measured yield and nitrogen content of the yield in March 1968 after good seasonal rainfall. Cleared pastures had potential nitrogen uptake of 16 kg N/ha in contrast to 12 kg N/ha for pastures under trees; and
4) detachment rates were estimated as 0.002 per day during the dry season (30% of May yield detaching in next 6 months) and 0.005 during the wet season (60% of November yield detaching over the next six months) from Ritson *et al.* (1971).

Independent validation was carried out using pasture data not used in model parameterisation (Figures 3 and 4). The simulation of pasture yield data was improved by allowing potential nitrogen uptake to vary as a function of rainfall. The cause of this result is uncertain and may reflect the importance of mineralisation from breakdown of organic material during above average wet seasons or possibly a variable contribution over time of nitrogen from the annual legume Townsville stylo.

The major errors in modelling Kangaroo Hills occurred in the high rainfall years of the mid 1970s (Figure 4). The main parameters that control growth under these conditions are potential nitrogen uptake and the minimum percentage of nitrogen required for growth to occur. In this simulation both are held constant. However variation between years can occur, for example, annual nitrogen uptake can change in response to increased decomposition of organic material in particular during warm/wet conditions. Nitrogen content was not measured during these years and hence it is not possible to determine the source of variation.

Kangaroo Hills was oversown with the pasture legume Townsville stylo. Although the establishment of the legume was not regarded as particularly successful, it did make a variable contribution to pasture yield and could have also contributed to the annual variation in nitrogen cycling.

Another alternative which would explain the errors in wet years is the change in minimum content of nitrogen required for growth as a result of changing leaf/stem ratios. The production of a large proportion of stem material requires less nitrogen per kg of dry matter and hence higher yields of low nitrogen concentration are likely to occur under good growing conditions.

This relatively poor understanding of the interaction between nitrogen cycling and pasture growth is thus reflected in our ability to adequately model these processes. We prefer to retain the simulation errors as clear outliers rather than 'calibrating' using other inappropriate parameters (e.g. transpiration efficiency or detachment rates). These 'un-modelled' processes operate under good conditions and hence are less likely to influence the simulation of drought conditions when most important interactions with stocking rate management occur. Because detachment and decomposition rates are high (e.g. McCaskill and McIvor 1993) possible errors made in simulating pasture growth in high rainfall years do not accumulate over time.

4.3 Changes in pasture composition

Continued heavy grazing results in changes in species composition usually with a decline in the percentage of desirable perennials. The change is simulated in this study by linking the percentage of desirable perennials to a yearly time scale (Figure 5) derived by Ash *et al.* (1996) from observed data. Grazing pressure is expressed as the percentage of total growth that is eaten as green material. We hypothesise, based on the rotational grazing work of D. Cooksley (unpublished data), that the heavy consumption of dead material (e.g. during the dry season) does not influence pasture composition.

The GRASP model includes the following pasture composition rules based on utilisation of green material by the end of growing season (30th April):

1) < 22.5% utilisation - percentage perennials increase by one perennial index year equivalent as in Figure 5;
2) > 22.5 but <35% utilisation - no change; and
3) > 35% utilisation - percentage perennials decrease by one perennial index year equivalent.

Thus continued grazing with more than 35% of total growth consumed as green material results in a decline from 90% perennials to zero over 11 years.

The loss of desired perennial grasses associated with heavy utilisation results in a change of pasture production (McIvor *et al.* 1995a, Day *et al.* 1997). The simulation of loss of production is achieved in GRASP by changing the model parameters. Field measurements and observations (e.g. Ash and McIvor 1995, Day *et al.* 1997), indicate that the following changes occur as the percentage of perennials decline from 90 to 0%:

1) the soil-water index threshold at which growth stops increases from 0.4 to 1.0;
2) maximum nitrogen uptake declines from 12 to 6 kg N/ha; and
3) minimum nitrogen content to which plants can dilute nitrogen and continue growth increases from 0.5% to 1% thus reducing overall nitrogen use efficiency.

These changes in parameters result in a reduction in average annual pasture growth from 1500 kg DM/ha to 600 kg DM/ha as percentage perennials decline from 90% to 0%.

This approach of linking functional parameters to species composition can be developed for most pasture communities. Using the Swiftsynd methodology (Day and Philp 1997) and exclosures placed on sites representing each pasture composition ‘state’, model parameters can be readily measured allowing simulation of production when the pasture is in each ‘state’ (e.g. Wandera 1993). Grazing studies on pasture composition using both grazier experience and grazing trials allow derivation of the rules for transition between states (e.g. Bisset 1962, Ash *et al.* 1994, 1996).

By this approach GRASP will in the future be linked to ‘state and transition’ models.

4.4 Soil loss model

In GRASP soil loss is calculated from run-off (Scanlan *et al.* 1996a) and the relationship between total soil concentration in run-off (bed load + suspended sediment) and cover (Scanlan and McIvor 1993). Scanlan *et al.* (1996a) drew attention to:

1) the danger of extrapolating soil losses derived from upper and mid-slope position to whole catchments;
2) the inherent variability in soil erodibility factors; and
3) the uncertainty regarding the effects of trees and fire on cover and surface infiltration properties.

As a result, cover alone is not the sole factor controlling run-off and erosion. In GRASP the effect of trees on surface cover is modelled as a minimum surface soil cover calculated from the relationship between maximum percentage bare ground and tree basal area (J. Carter unpublished data).

Soil loss for the month after burning is lower than that expected from a surface with low cover resulting from grazing and natural decomposition (McIvor *et al.* 1995b). In GRASP the effective surface cover used in calculating run-off and soil loss is not recalculated until 28 days after the fire. Thus effective surface cover remains constant at the pre-burn value.

5. Beef cattle production model in GRASP

For this simulation study we developed both monthly and annual LWG models. The annual LWG model was a multiple regression which simulated LWG for the June - May period. Data to develop the models came from three grazing trials:

1) Kangaroo Hills annual LWG data were available from 1965 to 1975 for the four treatments (data provided by R. Rebgetz). Steers varied in breed (Hereford or Brahman cross) and age (weaners or yearlings);
2) Galloway Plains, central Queensland, annual LWG data were available for six stocking rates from 1991 to 1993 for yearling steers on black speargrass (west repetition data provided by W. Burrows); and
3) Mt Bambling, Brian Pastures, data were available for 16 years for steers of three ages grazing an annually burnt black speargrass paddock (data provided by R. Roberton).

Thus the data available for developing an annual relationship covered a range of locations (over 1500km) in the coastal black speargrass zone, climatic conditions and stocking rates. GRASP had been previously calibrated for pastures at Galloway Plains and Mt Bambling following the same procedure described above for Kangaroo Hills (Day *et al.* 1997).

For Kangaroo Hills monthly liveweights were available for 1965 to 1971. Possible predictors were examined to simulate monthly LWG. The best predictors, evapotranspiration multiplied by a temperature-index from the previous month (ET ∗ TI, mm/day) explained 65% of observed monthly LWG (LWG_{ET}) across years and treatments (Figure 6a):

$$LWG_{ET} = 1.194 - 1.542 * e^{-0.6652 * ET * TI}$$

However, annual LWGs were over estimated using this approach (Figure 6b). For all data across the three locations the relationship between observed and predicted annual LWG from the monthly model ($ALWG_{ET}$) was:

$LWG = 0.126 + 0.529\ ALWG_{ET}$; ($r^2 = 0.62$, n = 76)

For Kangaroo Hills with trees not killed, the over-estimation was not as great but still indicated that errors accumulated with the monthly LWG model:

$LWG = 0.073 + 0.716\ ALWG_{ET}$ ($r^2 = 0.81$, n = 20)

This overestimation of annual LWG by the monthly LWG model indicates that short time-step (i.e. monthly) models of LWG are likely to incorrectly represent the possible effects of compensatory growth or gut fill change (McLean *et al.* 1983) which can led to accumulating errors in simulation of LWG over longer time periods.

Previous analyses had shown that a large proportion of year-to-year variation could be accounted by simple climatic indices such as length of the growing season (Gillard 1979, McCown 1980-81, McKeon *et al.* 1980, Jones *et al.* 1990, McCaskill and McIvor 1993). This approach has been used here to include the effect of stocking rate on animal production (McKeon *et al.* 1980, Rickert *et al.* 1981, McIvor and Moneypenny 1995).

For all three locations (Figure 7d):

LWG = 0.013 + 0.00535 ∗ %gidays - 0.0016 ∗ %utilisation ($r^2 = 0.69$, n = 72)

where LWG is annual liveweight gain (kg/hd/day),
%gidays is the percentage of days in the year with growth index $\geq$ 0.05,
%utilisation is $\frac{\text{pasture eaten over the year}}{\text{pasture growth over the year}}$ as a percentage.

The variable %gidays explained 59% of variation in LWG (Figure 7a) whilst %utilisation explained only 28% (Figure 7b) of the variation in LWG. The correlation between these variables was low ($r^2 = 0.09$) indicating that a reasonable combination of utilisation and growing conditions was covered (Figure 7c). This approach will be further developed to include the effects of phosphorus (McCosker and Winks 1994), supplements, burning and other environments such as the Mitchell grass downs in the arid zone.

The following relationship was derived for annual LWG specifically for Kangaroo Hills (treatments with trees, Figures 8a and b).

LWG = 0.0239 + 0.005586 ∗ %gidays - 0.00229 ∗ %utilisation (r^2 =0.80, n=20)

The stocking rate effect on LWG in this relationship is similar to that found by Ash and Stafford Smith (1996) in a review of stocking rate relationships in rangelands which showed a 20% decline in LWG per head for a 100% increase in stocking rate.

Examination of other possible variables was carried out. There was no effect of animal age; direct climatic effects (as represented by a temperature/humidity index, King 1983); pasture nitrogen concentration at the end of the growing season; or utilisation of previous year’s growth. This surprising lack of expected effects highlights the dominating influence of length of growing season (%gidays) and stocking rate (%utilisation) but also suggests that the possible variable contribution of legume limits further analysis.

The failure of shorter time step models to account for more of the geographic and year-to-year variation, when compared to the annual LWG model, shows that the importance of accounting for possible compensatory growth and gut fill effects in short time-step models. However, the problem of modelling seasonal changes remains to be investigated. Such models are required to allow within-year changes to stocking rate and for use in models of reproduction and mortality (Stafford-Smith *et al.* 1997).

The terms in the regression are also affected by grazing effects on pasture. Increasing utilisation reduces green cover and increases soil-water availability and hence the percentage of days when the growth index is above 0.05. Other modelling analyses of grazing trials (Day *et al.* 1997) have shown that the soil-water threshold at which growth stops increases with increasing pasture utilisation either due to reduced root activity or a change in species composition to early flowering species. In this model, the critical threshold for accumulating growth index days is changed from 0.05 to 0.20 as the percentage of desirable perennials decline to zero and hence heavy grazing has little effect on the percentage of growth index days greater than or equal to the critical threshold.

5.1 Extrapolation of LWG multiple regression

Although the multiple regression was established over a wide range of locations and rainfall variability, its application in the simulation of grazing strategies requires specific attention to the effects on LWG of:

1) intake restrictions due to low pasture yield;
2) effects of pasture burning; and
3) loss of desirable perennial grasses, i.e. poor pasture condition.

5.2 Intake restrictions

Intake restrictions occur when low pasture yield reduces bite size and animals are unable to compensate by increasing biting rate and/or grazing time. In tussock grasslands, restrictions are likely to occur below 200-500 kg DM/ha (Hendricksen *et al.* 1982) although no definitive data are available. In GRASP we have included a restriction on intake as part of modelling pasture yield under heavy grazing. We proposed the following relationship between relative intake (RI_1) and total standing pasture yield (TSDM):

$RI_1 = \min(1.0, TSDM / P_{144})$

where P_{144} is yield above which intake is not restricted by pasture availability.

By calibrating the model for heavily grazed pasture we have found that P_{144} is approximately 300 kg DM/ha for a range of black speargrass pastures grazed by British breeds of cattle (data from Scattini 1973).

The Kangaroo Hills trial provides a few months where simulated yields were less than 300 kg DM/ha. For these native pastures, weight loss had a linear relationship with pasture yield when the proportion of green in the pasture was low (< 10%, Figure 9). Thus, in the annual LWG model we also calculate weight loss when the above conditions occur using the relationship:

daily liveweight loss (kg) = TSDM / 300.0 - 1.0

These LWG data (Figure 9) from Kangaroo Hills may under estimate liveweight loss during the dry season because of the presence of high quality dead material from the annual legume Townsville stylo (Norman and Begg 1972).

GRASP also calculates a restriction on intake (RI_2) due to increasing utilisation since the start of the growing season (December 1) representing the effects of increased grazing time and declining availability of desirable pasture components (e.g. leaf) as utilisation increases:

$RI_2 = 1.0 - 0.30 * \underline{\%utilisation}$

100

The co-efficient (-0.30) has been derived from an analysis of average stocking rate relationships for a wide range of recent grazing trials (M. Quirk pers. comm.). This slope co-efficient is flatter than that found by McKeon and Rickert (1984) and that also derived from data for short term or rotationally grazed trials (Ash *et al.* 1995). A co-efficient of -0.4586 (McKeon and Rickert 1984) was used in GRASSMAN (Scanlan and McKeon 1990) to simulate LWG and hence produced a greater decline in LWG with increasing stocking rate than simulated here by GRASP.

The actual restriction on intake is the minimum of RI_1 or RI_2.

This approach of reducing simulated intake by either restrictions on pasture yield or declining availability of desirable pasture components allows reasonable simulation of pasture yield under heavy grazing and/or drought. However, a risk in modelling LWG from an annual multiple regression is that basic energy conversion limitations in converting pasture dry matter intake to LWG will be overridden. Hence in this model, we calculate an upper limit to annual LWG (LWG_{max} kg/ha/yr) for steers (200 - 350 kg liveweight) based on average daily dry matter intake per head (DMI, kg/hd/day) for the year:

$$LWG_{max} = 365 * (DMI * 0.304 - 0.800)$$

This relationship was estimated from model output and differs substantially from the relationship between intake and LWG given by Minson and McDonald (1987, Figure 10). These differences between intake - LWG relationships (e.g. McKeon and Rickert 1984, Minson and McDonald 1987, Coates 1995) are yet to be resolved.

5.3 Effect of pasture burning on LWG

Pasture burning is a common practice in black speargrass areas to control woody weeds, provide access to green feed following spring rains, and re-distribute grazing pressure within paddocks. Of the trials used to develop the LWG multiple regression only Mt Bambling was regularly burnt. The impact of burning on annual liveweight has been estimated as 15 kg/hd from the experiments of Ash *et al.* (1982) at Brian Pastures and from data of McLennan *et al.* (1986) at Swans Lagoon. In the multiple regression analysis the co-efficient for pasture burning effect on LWG derived for the Mt Bambling site (variable = 1) compared to the other sites (variable = 0) was 7 kg/hd although not significant ($P>0.05$). This lower than expected value may result from other site differences (e.g. phosphorus, legume presence, winter feed quality).

5.4 Effect of loss of desirable perennial grasses on LWG

The loss of desirable perennial grasses (DPGs) can result in reduced pasture production (McIvor *et al.* 1995a; Wandera 1993). Exceptions include cases where DPGs are replaced by unpalatable perennials such as wire grass (*Aristida* spp.) or rats tail (*Sporobolis* spp.). Simulation of pastures where DPGs have been replaced by unpalatable species would require modifications to the LWG multiple regression such that only the palatable production was included.

Ash and McIvor (1995) found that pasture quality may increase with a decline in pasture condition. In short term (8 weeks duration) grazing trials, poor-condition pastures had higher LWG/hd at low utilisation rates but had a greater decline in LWG/hd with increasing utilisation rate (Ash *et al.* 1995).

In the current simulation analysis we consider only the effects of changing pasture condition on pasture production in the LWG multiple regression. Thus for pastures in poor 'condition' but of high quality, such as annuals species, the model is likely to underestimate LWG/hd at low utilisation.

5.5 Effect of annual period on LWG

The annual LWG model was developed from LWG of drafts of steers grazed from the early dry season (June) or winter over the following 10-13 months. In the following studies the model will also be used to simulate LWG from November to October. As yet no validation data of steer growth for this period are available and hence we assume, not unreasonably, that the same variables (number of growing days and percentage utilisation) dominate LWG/hd. McCaskill and McIvor (1993) developed a similar type of model for an annual LWG period starting in February but as yet GRASP has not been compared with their analysis.

6. Qualitative model validation using property records and producer demonstrations

The experiences of one grazing property has been evaluated using this model. One of us (A. Ash) had access to annual property stocking rates since 1923 for a property near Charters Towers. Small adjustments to plant growth and soil-water parameters were made to the parameter set established for Kangaroo Hills. Actual total property stock numbers were converted to stocking rate (head/ha) from estimates of area of property grazed. An average liveweight of the herd of 410 kg, which determines pastures intake, was calculated from an average herd description based on age-of-turnoff of steers.

Rainfall at the homestead (an official Bureau of Meteorology recording station) and Charters Towers daily climate were used as climate inputs. The grazier commented that in some years large spatial variation in rainfall occurred across the property highlighting a potential difficulty in using property records to validate models.

Major changes in herd management included: a change in breed composition from *Bos taurus* to *Bos indicus* during the 1960s; and the increased use of urea/molasses supplements during the 1980s (Gardener *et al.* 1990). The change from *Bos taurus* to *Bos indicus* breeds was simulated by changing parameters describing animal intake. Cattle with a high component of *Bos indicus* were able to maintain intake at lower levels of pasture availability. This capability was represented by changing parameters restricting intake per head. The effects of supplementation on increasing intake were represented by increasing potential LWG in the dry season.

The model was evaluated by qualitatively examining simulation of TSDM, grass basal area, pasture composition, annual LWG, and stocking rate changes compared to pasture availability. Simulation of TSDM was regarded as reasonable especially during the severe drought periods when heavy destocking was required, e.g. 1987-88. Over all years (1923 to 1996) average simulated annual pasture utilisation was 20%. This safe utilisation value is supported by the property being in good condition. Simulation of grass basal area indicated greater variability than expected based on grazier experience. For example, the low grass basal area simulated during the 1960s due to sequences of dry years did not match grazier memory of pasture condition. However, simulation of pasture composition changes was regarded as reasonable with the actual and simulated pasture composition remaining in good composition through the recent (1991-96) drought period.

Whilst simulation of average annual LWG was reasonable, liveweight losses were overestimated. This is to be expected since the effects of supplementation, browse and landscape variability are not included in the multiple regression model which was established from small paddocks in grazing trials. During extended drought periods (e.g. 1991-96) the model may also underestimate LWG due to a failure to simulate changes in nitrogen availability. In the second and subsequent years of an extended drought period there is likely to be a buildup of mineral nitrogen and hence higher pasture quality as indicated by the proportion of leaf and the protein content of biomass. Clear evidence of these effects on LWG is not available in grazing trial data as yet but is supported by anecdotal evidence of graziers. These multi-drought conditions have occurred in 11% of years (12 out of 108 years).

The qualitative validation using producer data indicated that the simulation of TSDM is reasonable with drought periods identified. The model overestimates liveweight losses because no attempt is made to include the impact of supplementation. Thus the simulation of liveweight losses is best regarded as identifying periods when supplementation would be required.

A standard validation test of a model is that it should be able to identify possible errors in inputs such as daily rainfall and stocking rates. In this case a major simulation anomaly (low simulated TSDM of 200-300 kg DM/ha in 1970) was likely to be due to missing data in the daily rainfall file obtained from the Bureau of Meteorology/Rainman data set. The source of error has not been found but may in fact be a failure in reporting or distinguishing between dry months and missing data. All neighbouring rainfall stations received significantly higher rainfall than this property in 1969-70. Given that there was no destocking indicated in property records, the error is more likely to be in the rainfall record rather than in the model!

6.1 Property stocking rate records and simulated pasture availability

Actual property records indicated that stock numbers peaked in 1982 at 80% above the long term average. The subsequent below-average rainfall period 1983-84 to 1987-88 included four years (1982-83, 1983-84, 1986-87, 1987-88) in which stock numbers were reduced. The percentage reduction in stocking rate (SR) was calculated as:

$$\% \text{ reduction in SR} = 100 * \left(1 - \frac{\text{this-year's-SR}}{\text{last-year's-SR}}\right)$$

For these four years there was a strong linear relationship ($r^2 = 0.99$, $n = 4$) between the simulated minimum TSDM for the year and the percentage reduction in stocking rate (Figure 11). This suggests the model can simulate reasonably accurately the feed availability criteria that graziers respond to in making destocking decisions.

We hypothesise that ‘forced’ destocking decisions in response to low pasture availability are likely to result in more stress for animals and pastures, unlike pro-active decisions to reduce stock numbers in anticipation of future feed deficits. The latter decision can be made whilst stock are in reasonable condition and without unnecessary damage to pasture. Thus the simulation of minimum pasture availability is a key criteria for comparing grazing strategies in terms of ‘forced destocking’.

6.2 Conclusion

The model provides a reasonable simulation of year-to-year variation in pasture availability especially under drought conditions while errors due to the model’s assumptions are most likely to occur in above-average years. However, the rapid pasture detachment rates in this environment (Ritson *et al.* 1971, Gardener *et al.* 1993) reduce the likelihood of errors from simulating pasture production in above-average years carrying over to subsequent years.

6.3 Validation with Producer Demonstrations at ‘Thalanga’

A preliminary comparison was made between results from ‘Thalanga’ grazing trial and the model using Charters Towers rainfall and soil/plant/trees/animal parameters derived from Kangaroo Hills data. Actual rainfall data and soil/pasture parameters were not available at the time of this study. The native pasture treatment was grazed at stocking rates to eat ‘30% of feed available at the end of the grazing season’. From 1984 to 1991 average yield was 1135 kg DM/ha compared to a simulated average yield of 1318 kg DM/ha; average stocking rate was 6.9 ha/steer compared to a simulated value of 7.9 ha/adult equivalent; and average LWG was 86 kg/hd compared to a simulated value of 145 kg/hd.

A complete analysis of this grazing trial will require accurate estimates of the model parameters especially soil fertility given the low phosphorus status at Thalanga (McCosker and Winks 1994). Resolution of the differences between stocking rates and LWG will require a more thorough analysis of actual data including definition of animal units. The large difference in LWG/hd may be due to: a) the limitation imposed by low soil phosphorus (P level of 2-3ppm); b) the poorly structured yellow earth; and c) the likely lower rainfall compared to Charters Towers.

6.4 Validation of soil loss

Soil loss for a cleared paddock (14.2 ha) at Kangaroo Hills has been measured at 1.9 t/ha/yr using the caesium 137 technique (Elliot *et al.* 1996). At this stage of documentation it is not possible to reconstruct the grazing history and slope of this particular paddock. Instead we have simulated soil loss from a paddock grazed by *Bos indicus* cattle with stocking rate adjusted each year in June to eat 50% of TSDM. The simulated soil loss from 1966 to 1988 was 1.92 t/ha/yr. This simulation was not calibrated in any way to achieve this remarkable validation. Reconstruction of actual grazing history including supplementation and legume contribution will allow a more formal validation. This remarkable agreement may be fortuitous and hence simulated soil loss should still be treated in relative terms when comparing grazing strategies.

7. Simulation studies of grazing strategies

Five general grazing strategies were tested for a range of utilisation rates. The base simulation was that of an exclosure which was annually mown as in the GUNSYNpD experimental methodology (McKeon *et al.* 1990). On November 1^{st} each year yields were reset to 100 kg DM/ha green material and 200 kg DM/ha dead material as if the pasture was mown. Average annual growth was calculated over the simulation period. Pasture growth in individual years was stored and used to provide the basis for a 'perfect' forecast strategy.

7.1 Strategy 1 *'Constant' utilisation of long term average growth*

Stocking rate was calculated to eat a constant proportion of long-term average annual growth as calculated from the previous simulation of exclosure pasture growth. Thus stocking rate does not change from year-to-year.

7.2 Strategy 2 *'Reactive' based on June pasture yield*

Each year stocking rate was changed in June to eat a constant proportion of existing TSDM over the next 12 months. No estimate of future growth was included in the calculation.

7.3 Strategy 3 *'Perfect knowledge'*

Each year stocking rate was changed in June to eat a constant proportion of a perfectly known pasture growth. The 'perfect forecast' pasture growth had been previously calculated in the initial simulation of an exclosure as described above. Stocking rate affects pasture growth during the growing season and hence the approach adopted here was to establish a multiple regression to estimate intake (kg DM/ha) and actual pasture growth as a function of both stocking rate and 'perfectly known' pasture growth in an exclosure. The regressions below were solved iteratively to find the stocking rate which resulted in the desired constant utilisation of predicted pasture growth:

$$\text{predicted growth (t/ha)} = 0.744 + 0.804 * \text{growth} + 0.01429 * \%\text{perennials} + 0.0030565 * \text{TSDM} - 0.002397 * \text{SR}$$

$$\text{predicted eaten (kg DM/ha)} = 1.4725 * \text{SR} * (0.0235 * \text{TSDM} + 1) * (0.2943 * \text{growth} + 1) * (0.06996 * \%\text{perennials} + 1)$$

where growth is pasture growth (t/ha),
TSDM is total standing dry matter (t/ha),
%perennials is the percentage of perennials in TSDM,
SR is stocking rate (hd/100 ha).

By iteratively solving these equations for different stocking rates, the intended stocking rate can be found which achieves the target utilisation:

$$\text{desired SR} = 100 * 0.01 * \frac{\text{predicted eaten}}{\text{predicted growth}}$$

This approach was adopted to speed up simulation. Whilst it does not result in precisely the target utilisation every year, on average the target utilisation is reached with a co-efficient of variation (CV) of 17% across targets of 10-40% utilisation compared to CVs of 55 and 64% for constant and reactive strategies respectively.

The alternative approach of running the model forward in time each year to iteratively find the actual stocking rate that would achieve exactly the intended utilisation has been implemented in Working Paper 9 (Stafford Smith *et al.* 1997). The version of GRASP used here was not capable of this approach.

7.4 Strategy 4 *'SOI - forecast' in November*

Stocking rate was changed each year in November based on the value of the SOI recorded during the previous three months (August - October). Three types of year were identified (after Clewett *et al.* 1988): SOI < -5; SOI between -5 and +5; and SOI > +5. A stocking rate was calculated to eat a varying proportion of long-term average growth with the stocking rate able to be modified in November for a given SOI year type. For example, a stocking rate would be calculated to eat 30% of long term average growth. This calculated stocking rate would be increased or decreased in November by 50% for SOI > +5 and SOI < -5 year types respectively. No change to the calculated stocking rate would occur where the August - October SOI was between -5 and +5.

7.5 Strategy 5 *'Increased SOI forecast lead-time' in June*

Stocking rate was changed each year in June, as in strategy 2, to eat a varying proportion of TSDM. The calculated stocking rate would then be adjusted for SOI year types as identified in strategy 4. For example, a stocking rate would be calculated each June to eat 40% of current TSDM. This calculated stocking rate would be increased or decreased by 50% for SOI > +5 and SOI < -5 year types respectively. No change to the calculated stocking rate would occur where the March - May SOI was between -5 and +5.

Only low forecasting capability is available for N.E. Queensland in June using the SOI recorded during the previous three months (March-May) to predict summer rainfall (Figure 12). However, since 1982 forecasts of El Niño development have been made with some skill from May onwards. Recently, e.g. 1986, 1990 and 1995, forecasts of El Niño development have been made up to a year beforehand. In this strategy we are assuming that SOI information available in June has as much skill as the SOI available in November (strategy 4) for the forecasting of summer rainfall. Thus there is an increase of five months (June ← November) in the lead-time of forecast skill allowing graziers to utilise SOI information in June for stocking rate decisions.

8. Simulation Results

Figure 13 and Table 1 summarise the simulation results from over 100 simulation treatments (referred to as treatment #) including combinations of grazing strategies (*perfect-knowledge, reactive, constant, SOI forecast, increased SOI forecast lead-time*); intended utilisation rates (0-60%) of long-term average growth, known annual growth, forecast growth or total standing dry matter; and month of stocking rate change (June or November).

The modelled output variables were averaged over the period of simulation and included:

1) components of soil-water balance, i.e. run-off, drainage, tree water use, soil evaporation and grass transpiration;
2) pasture variables, i.e. pasture growth, TSDM at time of stocking rate change (June 1st or November 1st), grass basal area, number of fires, and minimum TSDM at any time in the year;
3) animal intake and numbers, i.e. amount eaten, annual utilisation, stocking rate and standard deviation of stocking rate; and
4) animal production variables, i.e. LWG/hd, LWG/ha, liveweight loss, and percentage of years with annual LWG less than 100 kg/hd.

The variable LWG/ha has been calculated each year and then averaged over the 107 years. Hence in Tables 1-3, average LWG/ha does not equal average LWG/hd multiplied by stocking rate (hd/ha). In contrast average annual utilisation in Tables 1-3 and Figure 13 was calculated as the ratio of pasture eaten (kg DM/ha) averaged over 107 year to pasture growth averaged over the same time period. Across all strategies average annual utilisation and stocking rate were highly correlated (Figure 13c, r^2=0.996, n=31) and hence utilisation has been used to compare response surfaces (Figure 13).

8.1 Liveweight gain per ha

The highest LWG per ha (LWG/ha) of 29.2 kg in treatment #1 was achieved at an intended utilisation of 40% of predicted annual (June-May) growth, i.e. '*perfect knowledge*'. Above this utilisation level the composition of desired perennials declined and production of both pasture and animals was greatly reduced (Figures 13a and b).

There was 1.9 kg/ha difference in maximum LWG/ha between times of stocking rate change (June treatment #1 compared to November treatment #12). For stocking rate change in November an intended utilisation of 40% and above resulted in detrimental pasture composition changes but intended utilisation of 40% of annual growth starting in June could be achieved without such effects. This is likely to be an artefact of the model resulting from the fact that potential nitrogen availability is reset each year at the end of the dry season (November 1st). Thus annual growth (Nov-Oct) has a maximum possible growth of 2068 kg DM/ha/yr whilst the period June-May can result in higher values. The development of continuous functions to simulate nitrogen mineralisation to replace the resetting date of nitrogen availability in the model is likely to eliminate this artefact. At lower intended utilisation, e.g. 30% (treatment #2 and #13) there was less difference (0.1 kg LWG/ha) between June and November stocking rate change.

Maximum LWG/ha for *perfect knowledge* (29.2 kg LWG/ha) exceeded the best production from the *reactive* strategies (treatment #3) by 4.9 kg/ha and the best *constant* stocking rate (treatment #6) by 8.9 kg/ha. These latter two treatments (#3, #6) had average LWGs per head (LWG/hd) of 79 and 76 kg respectively, which would be too low to ensure turn-off of steers at a 'reasonable' age, e.g. to turn-off 450 kg steer at 42 months from a weaning weight of 150 kg would require an average of 100 kg LWG/hd/yr.

The 40% utilisation *reactive* treatment (#4) averaged 96 kg LWG/hd whilst the *constant* stocking rate treatment intended to utilise 30% of average growth (#7) averaged 101 kg/hd/yr. The latter treatment (#7) is the 'safe' stocking rate treatment as calculated using the method proposed by Scanlan *et al.* (1994) and found to agree well with graziers' estimates of safe stocking rates. Thus for treatments averaging approximately the same LWG per head

(96-101 kg LWG/hd), LWG per ha was 29.2, 23.1 and 20.2 kg LWG/ha for *perfect knowledge*, *reactive* and *constant* stocking rate respectively.

Six SOI-forecasting treatments were simulated. For a change in stocking rate in November, the *constant* stocking rate calculated to utilise 30% of long-term average growth was adjusted each year based on the SOI for the previous August to October: 50% reduction in stocking rate when SOI ≤ -5; and 50% increase in utilisation when SOI ≥ +5. LWG per ha (21.3 kg/ha, #19) exceeded the best *constant* rate treatment (#14) by 1.4 kg LWG/ha or 7% (1.4/19.9). Greater advantages were achieved when stocking rates were increased only in La Niña years (treatment #18). However, *SOI-forecast* strategies in November (#17-19) had lower LWG/ha than *reactive* strategies in June.

The value of achieving the same forecasting skill in June as is now available in November (i.e. *increased SOI forecast lead-time* strategy) was evaluated in treatment #11. Stocking rate was changed in June to eat 40% of TSDM over the next 12 months as in treatment #4 with a 50% reduction in El Niño years when SOI ≤ -5 averaged from August to October, and 50% increase in La Niña years when SOI ≥ +5 averaged from August to October. Compared to the *reactive* strategy the *increased SOI forecast lead-time* strategy improved LWG per ha by 9% from 23.1 (treatment #4) to 25.2 kg (treatment #11) and increased the proportion of years in which a LWG of 100 kg/hd was achieved from 57% to 63%.

8.2 Risk of liveweight loss and low pasture yield

The risk of liveweight loss and running out of pasture was evaluated with a range of variables: average annual liveweight loss over the 100 years; lowest pasture yield; and decile 1 pasture yield. Compared to *perfect knowledge*, the *reactive* and *constant* strategies which maximised LWG/ha (treatments #3 and #6), resulted in at least twice the risk of weight loss (-4 compared to -8 and -11 respectively). Reducing the intended utilisation rate for the *reactive* strategy from 40% to 30% of TSDM halved the average liveweight loss and substantially reduced the risks when expressed in terms of lowest TSDM. Reducing the intended utilisation in the *constant* stocking rate treatment similarly reduced risks of liveweight loss but not as much as the *reactive* treatment.

Both SOI forecasting treatments (#11 and #19) reduced risks of liveweight loss compared to their comparative constant treatments (#4 and #7 respectively). Of the above strategies the (*increased SOI forecast lead-time* strategy*)* produced the lowest average and extreme liveweight loss, the highest minimum TSDM, and highest average LWG/ha achieving 86% (25.2/29.2) of the potential LWG/ha, i.e. that achieved with *perfect knowledge* of annual pasture growth.

8.3 Resource condition

The three indicator variables of resource condition were grass basal area, percentage years with a fire and average soil loss. The impact of changing grass basal area has been modelled through the effects on pasture growth, utilisation and LWG. The effect of fire frequency on woody weed regrowth and effect of soil loss on infiltration, nutrient availability and available water range have not been simulated in the studies.

In these simulations, 33% of the pasture was burnt if yield exceeded 1200 kg DM/ha. Thus a fire frequency of over 30% of years is required to ensure each location is burnt at least once in ten years. Only the safe *constant* stocking (#7) and the *SOI-forecast* in November strategy (#19) achieved this frequency of burning. As would be expected, treatments which maximised LWG/ha minimised the frequency of burning (Figure 13m).

Similarly, soil loss and LWG/ha were related with soil loss generally increasing with LWG/ha. However, for the treatments (#1, #3 and #6) which maximised LWG/ha, soil loss was similar, 1270 to 1333 kg/ha/yr. The more conservative utilisation rates and the SOI forecasting strategies (#11 and #19) had similar soil loss, 1022 to 1096 kg/ha/yr.

Thus the *increased SOI forecast lead-time* strategy, when compared to the safe *reactive* treatment (#4), had increased LWG per head and reduced risk of liveweight loss but only allowed a frequency of burning of one in twenty years (0.16 ∗ 0.33) and increased soil loss by 4% (1062/1022).

8.4 SOI forecasting strategies

The above analysis highlights the trade-off between increased production of LWG per ha and increased risk of feed shortage, reduced fire frequency and increased risk of soil loss. Adjusting strategies by including SOI information (or perfect SOI predictions) resulted in increased production (7-9% respectively) without substantial increase in risk of resource damage, and, in the case of pasture availability, substantially reduced risk of running out of feed.

Further examination of both the June and November SOI forecasting strategies showed that increasing stocking rate only in La Niña years increased liveweight per ha by 8 (1.9/23.1) or 13% (2.5/19.9) respectively but substantially increased soil loss and reduced frequency of fires. Alternatively, reducing stocking rate only in El Niño years reduced LWG/ha by 0 and 6% but reduced soil loss from 1022 to 995 kg/ha/yr (2%) and 1112 to 992 kg/ha/yr (11%), and increased frequency of fires from 12 to 22% and 33 to 39% respectively. Such reductions in risk of irreversible damage to the resource are likely to outweigh production losses. Reduction of stocking rate in only El Niño years also increased average LWG per head from 96 to 105 kg and 99 to 110 kg, and increased the percentage of years with LWG/hd greater than 100 kg from 57% to 68% and 67% to 74% respectively. Similar reductions in risk to resource condition and feed shortage could also be achieved by strategies resulting in lower stocking rates, e.g. 30% use of TSDM (treatment #5) or *constant* stocking rate to eat 20% of average growth (treatment #16). However, in the latter cases the overall reduction in stock numbers results in lower production (LWG/ha) than only reducing stocking rates in El Niño years (20.7 compared to 23.0 kg/ha and 15.6 compared to 18.7 kg/ha).

8.5 Impact of stocking rate adjustment for El Niño years

The impact of adjustment of stocking rate for El Niño years (SOI ≤ -5 in August-October) was examined by modification of two existing strategies:

- for the June *reactive* strategy a stocking rate was calculated to eat 40% of TSDM. In El Niño years only, this stocking rate was multiplied by a constant value ranging from 0.25 to 1.25 for simulation treatments #1-5, (Table 2); and
- for the *constant* strategy where stocking rate was calculated to eat 30% of long term average annual growth. In El Niño years only, this stocking rate was multiplied in

November by a constant value ranging from 0.25 to 1.25 for simulation treatments #6-10, (Table 2).

Table 2 shows the impacts of stocking rate adjustments for El Niño years. For *reactive* stocking rate changes in June, a reduction in stocking rate in El Niño years did **not** substantially reduce LWG/ha but in fact a 25% reduction in stocking rate (i.e. multiple 0.75) slightly increased LWG/ha as well as increasing LWG/hd, reduced the risk of weight loss (by 31% from -3.9 to -2.7), increased the minimum TSDM (up by 28%) and reduced soil loss (down by 3%).

For changes in stocking rate in November, a 25% reduction in stocking rate in El Niño years only resulted in a 2% reduction in LWG/ha, a 22% reduction in average liveweight loss, and smaller reductions in risk of minimum TSDM and soil loss. To achieve substantial (>10%, 992/1112) reductions in soil loss, greater reductions (50%) in stocking rate in El Niño years were required which also reduced LWG/ha by 6%. The same stocking rate reduction (50%) in La Niña years only (SOI ≥ +5 in August-October) resulted in a reduction in soil loss of only 4% (1022/1112, results not tabulated) highlighting the importance of reduced stocking rate in El Niño years.

We would regard the simulation of these irreversible soil losses as conservative since no feedbacks on soil physical (e.g. infiltration) or biological (loss of soils nutrients) attributes are simulated as yet. On some sealing soils, exposure of surface soil to direct rainfall impact is likely to lead to surface sealing. Similarly the effects of heavy grazing can lead to surface structure changes resulting in reduced infiltration (Williams and Charters 1991). If these effects were included then the advantage of reducing stocking before, rather than after, seasons of low pasture growth would be more advantageous than simulated in these studies.

Table 3 compares treatments which have approximately the same average stocking rate (19-21 head/km^2). Compared to the *constant* stocking rate, eating on average 30% of long-term average growth, changing stocking rate each year to eat a constant proportion of known future growth (*perfect knowledge*) increased LWG/ha by 22%. There was a small benefit of *reactive* stocking rate strategy (+2%) while the *increased SOI forecast lead-time* strategy increased LWG/ha by 14%. The strategy of changing stocking rate in November based on previous August-October SOI increased LWG/ha by 5%. Compared to the reactive treatment (#5), the November SOI strategy had the same year-to-year variation in stocking rate but increased the risk of liveweight loss and increased soil loss. More work is required to clarify this result.

Table 4 shows the stocking rates used in each year type (El Niño or La Niña) for the different strategies. The *perfect knowledge* strategy resulted in a 19% reduction in stocking in the 35 El Niño years and a 24% increase in the 30 La Niña years. The *reactive* strategy was not correlated with SOI at all and hence average stocking rates in each type were the same. The two SOI strategies of course used the year type to determine stocking rate and reflect this link. Thus, the *reactive* strategy is likely to be one year out in responding after a drought or good year. However, where poor or good years occur in a sequence, the *reactive* strategy is likely to have benefits over an *SOI-forecast* strategy with imperfect skill (r^2= 0.16 - 0.25).

The possible non-random runs of good or poor years at Charters Towers is yet to be explored but long sequences of good and poor pasture growth years have occurred, for example:

- good runs, 1953-4 to 1959-60 and 1970-71 to 1981-82; and
- poor run, 1991-92 to 1995-96.

Future simulation studies will concentrate on evaluating to what extent the November *SOI-forecast* strategy can be improved by using other variables (such as TSDM, grass basal area) known at the time of the stocking rate decision (i.e. November).

A major outcome of the simulation studies was that varying the *reactive* stocking rate strategy in June **with an increased SOI forecast lead-time** would increase LWG/ha by 9% (25.2/23.1), reduce the risk of liveweight loss by 57% (from -3.9 to -1.7 kg/hd), reduce risk of low pasture yield, but would increase the risk of soil loss (+4%). Alternative strategies could also be developed which could reduce soil loss by 7% (955/1022) without reducing production (LWG/ha). There were small advantages for the best *reactive* strategy (#4) over strategies using current SOI skill (#19). This result was surprising and will be the subject of future work.

9. Issues for further modelling

The following issues will require further experimental and modelling work.

9.1 Liveweight gain model

An annual multiple regression LWG model was developed for this simulation study. The data included in the model were from steers grazed from June to May and hence included: (1) any potential compensatory growth as a result of previous poor seasons and restricted growth; and (2) potential weight loss during winter months. The application of this equation to an annual period from November to October, as used in this paper, has not been validated as this period does not correspond to any available experimental data.

The annual LWG model is also limited in not allowing steer growth to be simulated for shorter time periods, e.g. wet and dry seasons. Hence in this study it was not possible to simulate the effects of several stocking rate changes in a year.

Thus the development of an accurate shorter time step model of LWG is a priority. Such a model will have to include known sources of variation such as management, supplementation, climate (more correctly weather), pasture, genetics and previous grazing history. Of particular importance to the above studies is the modelling of the following effects of LWG:

1) supplementation to prevent animal weight loss and death;
2) compensatory gain after severe weight loss;
3) reduced metabolic demand in response to low nutrition;
4) contribution of browse, forbs and legumes to diet;
5) effect of pasture phenology and composition on diet quality including effects of drought and pasture burning; and
6) effect of extreme wet weather on animal grazing behaviour, metabolic demand, pasture quality, pests and diseases.

The LWG model used in these studies does not include explicitly any of the negative effects of high rainfall listed above. Hence the model could over-estimate production in these years and hence over-estimate the advantage of stocking up in response to or anticipation of these high rainfall seasons. However, the Kangaroo Hills LWG data did include 1973-74 which had an extremely wet summer. The observed LWG for this year was adequately simulated or even under-estimated by the multiple regression model (Figure 8b). Nevertheless, greater attention should be given to producer experience in regard to the impact of extreme years so that the risks of extreme events are correctly evaluated.

9.2 Resource Condition

The model highlights the trade-off between production (LWG/ha) and resource condition (frequency of burning and soil loss). Generally the treatments which increased LWG/ha decreased resource condition as a result of increased utilisation of grass production which reduced fuel for burning and soil surface cover.

Models of these feedbacks on production are required so that the trade-off can be better calculated by expressing different attributes in production terms (LWG/ha or $). Frequency of burning is likely to affect woody weed regrowth and equations to simulate these effects have been developed elsewhere (Scanlan and McKeon 1990, Burrows 1995). However, models are yet to be developed to simulate:

1) the effect of grazing on woody weed regrowth and tree survival under drought conditions (Scanlan *et al.* 1996b);
2) the suppressive effect of large existing trees on *Eucalypt* seedlings (K. Day pers. comm.); and
3) the invasion of weeds including rubber vine and chinee apple.

In the case of soil loss, models of feedbacks on infiltration (Holt *et al.* 1996) and nutrient availability are required. Soil attributes such as erodibility and nutrient profile of surface soil will be required and are likely to be site specific.

The possible link between grass basal area and infiltration (K. Day pers. comm.) has not yet been modelled. The run-off model (Scanlan *et al.* 1996a) uses only cover (calculated from TSDM and tree basal area). The work of McIvor *et al.* (1995) showed that burning of surface cover did not immediately increase run-off and soil loss. This aspect has been included in GRASP and could also be adapted to include the possible beneficial effects of high grass basal area on infiltration.

A variety of dynamic grass basal area models have been developed from grazing trials across Queensland (Day *et al.* 1997). A relatively simple model was used here in which grass basal area was calculated each April as a function of average pasture growth over the previous two years. This approach does include some of the effects of grazing but essentially represents a very resilient pasture. It is possible that pastures in which grass basal area is more sensitive to heavy utilisation in drought are more likely to be more productive if damage is avoided through the use of seasonal forecasts. Thus the development of better grass basal area models may give a different ranking to the grazing strategies than was simulated in this paper.

'More work is required'

Table 1. Results of simulation of grazing strategies.

#	Treatment	Study	Mean annual LWG/ha (kg)	Stocking rate (hd/km^2)	CV of stocking rate (%)	Utilisation (%)	Mean annual LWG/hd (kg)	% of years LWG/hd < 100 kg	Mean annual wt loss (kg/hd, eq. 6)	Worst weight loss for one year (kg/hd)	Decile 1 weight loss (kg/hd)	Worst TSDM (kg/ha)	Decile 1 TSDM (kg/ha)	% of years able to burn	Annual soil loss (kg/ha)
June change in stoking rate															
1	Perfect 40%	13 J	29.2	27.8	36	38	99	48	-4.0	-94	-10	77	150	9	1333
2	Perfect 30%	9 J	24.7	21.0	36	29	112	33	-2.5	-63	-1	109	247	31	1064
3	Reactive 60%	22 J	24.3	31.2	47	42	79	57	-8.3	-116	-34	79	146	1	1349
4	Reactive 40%	20 J	23.1	24.3	41	33	96	43	-3.9	-145	-5	83	231	12	1022
5	Reactive 30%	19 J	20.7	19.3	40	27	107	33	-2.4	-111	-3	106	242	36	975
6	Constant 40%	28 J	20.3	26.7	0	35	76	47	-11.0	-169	-43	6	110	18	1270
7	Constant 30%	27 J	20.2	20.0	0	27	101	36	-7.1	-132	-16	48	167	44	1091
8	Constant 20%	26 J	15.6	13.4	0	18	117	28	-3.8	-88	0	88	286	60	908
9	Reactive&SOI-50%	34 J	23.0	21.4	49	30	105	32	-1.4	-69	0	135	282	22	955
10	Reactive&SOI+50%	44 J	25.0	26.5	46	36	93	46	-4.1	-145	-8	83	220	6	1128
11	Reactive&SOI±50%	5B J	25.2	23.9	58	33	102	37	-1.7	-69	-1	135	271	16	1062
November change in stocking rate															
12	Perfect 35%	10 N	27.3	25.1	33	37	102	45	-2.2	-81	-1	107	224	6	1199
13	Perfect 30%	8 N	24.8	21.6	33	32	109	36	-1.4	-60	0	139	294	14	1009
14	Constant 40%	19 N	19.9	26.9	0	37	74	50	-12.4	-277	-44	6	82	8	1320
15	Constant 30%	18 N	19.9	20.2	0	29	99	33	-7.4	-121	-26	50	134	33	1112
16	Constant 20%	17 N	15.6	13.4	0	20	116	22	-4.3	-97	-12	75	213	55	920
17	SOI Forecast -50%	39 N	18.7	16.9	28	25	110	26	-4.0	-79	-14	72	172	39	992
18	SOI Forecast +50%	49 N	22.4	23.0	20	33	95	39	-7.6	-124	-28	49	121	27	1236
19	SOI Forecast ±50%	5B N	21.3	19.7	40	29	106	32	-3.9	-79	-12	71	166	29	1096

Perfect 40%: stocking rate changed to eat 40% of known future pasture growth over the next year
Reactive 40%: stocking rate changed to eat 40% of June standing dry matter over the next year
Constant 40%: stocking rate held constant to eat 40% of long-term average growth
Increased SOI forecast lead-time -50% or SOI forecast -50%: stocking rate reduced by 50% in El Niño years below base treatment
Increased SOI forecast lead-time +50% or SOI forecast +50%: stocking rate increased by 50% in La Niña years above base treatment
Increased SOI forecast lead-time ±50% or SOI forecast ±50%: stocking rate reduced by 50% in El Niño years and increased 50% in La Niña years compared to base treatment.
For June the base treatment was stocking rate changed to eat 40% of pasture standing dry matter and multiplied by 0.5 in El Nino years and 1.5 in La Niña years.
For November the base treatment was stocking rate set to eat 30% of long-term average pasture growth and multiplied by 0.5 in El Niño years and 1.5 in La Niña years.

Table 2. Results of simulation of grazing strategies for different stocking rate changes in only El Niño years.

#	Stocking rate multiplier used in El Niño years only	Study	Mean annual LWG/ha (kg)	Stocking rate (hd/km^2)	CV of stocking rate (%)	Utilisation (%)	Mean annual LWG/hd (kg)	% of years LWG/hd < 100 kg	Mean annual wt loss (kg/hd, eq. 6)	Worst weight loss for one year (kg/hd)	Decile 1 weight loss (kg/hd)	Worst TSDM (kg/ha)	Decile 1 TSDM (kg/ha)	% of years able to burn	Annual soil loss (kg/ha)
June change in stoking rate															
1	0.25	33	22.2	19.8	61	28	110	31	-0.7	-25	0	180	295	27	924
2	0.50	34	23.0	21.4	49	30	105	32	-1.4	-69	0	135	283	22	955
3	0.75	35	23.3	22.9	42	31	100	38	-2.7	-111	-4	106	244	18	990
4	1.00	36	23.1	24.3	41	33	96	43	-3.9	-145	-5	83	231	12	1022
5	1.25	37	22.4	25.6	44	34	92	45	-4.2	-103	-8	102	213	10	1073
November change in stocking rate															
6	0.25	38	17.4	15.2	47	22	115	24	-2.6	-46	-7	72	208	43	921
7	0.50	39	18.7	16.9	28	25	110	26	-4.0	-79	-14	72	172	39	992
8	0.75	40	19.5	18.5	13	27	104	30	-5.8	-102	-19	72	152	37	1073
9	1.00	41	19.9	20.2	0	29	99	33	-7.4	-121	-26	50	134	35	1112
10	1.25	42	20.2	21.8	11	30	95	38	-7.7	-138	-23	34	117	29	1161

For June the base treatment was stocking rate changed to eat 40% of pasture standing dry matter and multiplied by 0.25-1.25 only in El Niño years (treatments 1-5).
For November the base treatment was stocking rate set to eat 30% of long-term average pasture growth and multiplied by 0.25-1.25 only in El Niño years.

Table 3. Summary of grazing treatments with approximately same average stocking rate.

#	Treatment	Study	Mean annual LWG/ha (kg)	Stocking rate (hd/km^2)	CV of stocking rate (%)	Utilisation (%)	Mean annual LWG/hd (kg)	% of years LWG/hd < 100 kg	Mean annual wt loss (kg/hd, eq. 6)	Worst weight loss for one year (kg/hd)	Decile 1 weight loss (kg/hd)	Worst TSDM (kg/ha)	Decile 1 TSDM (kg/ha)	% of years able to burn	Annual soil loss (kg/ha)
June change in stoking rate															
2	Perfect 30%	9 J	24.7	21.0	36	29	112	33	-2.5	-63	-1	109	247	31	1064
5	Reactive 30%	19 J	20.7	19.3	40	27	107	33	-2.4	-111	-3	106	242	36	975
7	Constant 30%	27 J	20.2	20.0	0	27	101	36	-7.1	-132	-16	48	167	44	1091
9	Reactive&SOI-50%	34 J	23.0	21.4	49	30	105	32	-1.4	-69	0	135	282	22	955
November change in stocking rate															
19	SOI Forecast ±50%	5B N	21.3	19.7	40	29	106	32	-3.9	-79	-12	71	166	29	1096

Perfect 30%: stocking rate changed to eat 30% of known future pasture growth over next year
Reactive 30%: stocking rate changed to eat over the next year 30% of June standing dry matter
Constant 30%: stocking rate held constant to eat 30% of long-term average growth
Increased SOI forecast lead-time -50% stocking rate reduced by 50% in El Niño years below base treatment of *reactive* 40%
SOI forecast ±50%: stocking rate reduced by 50% in El Niño years and increased 50% in La Niña years compared to base treatment of 30% *constant*.

Table 4. Stocking rate is different year types* for different grazing strategies.

#	Treatment	Study	Stocking rate (hd/km^2)	CV of stocking rate (%)	Stocking rate in El Niño years (hd/km^2)	Stocking rate in La Niña years (hd/km^2)	Stocking rate in 'other' years (hd/km^2)
2	Perfect 30%	9 J	21.0	36	17	26	21
5	Reactive 30%	19 J	19.3	40	19	19	20
7	Constant 30%	27 J	20.0	0	20	20	20
9	Reactive + SOI -50%	34 J	21.4	49	12	26	26
19	SOI Forecast ±50%	5B N	19.7	40	10	30	20

*35 El Niño years when SOI ≤ -5 for August-October
30 La Niña years when SOI ≥ +5 for August-October
43 'other' years when -5 < SOI < +5 for August-October

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APPENDIX 1

Tasks yet to be completed (May 1998).

1. Grass basal area model to include utilisation.
2. Validation test on individual years at Thalanga PDS.
3. Include stocking rate strategy derived from (a) animal numbers history and (b) Scanlan *et al.* 1994.
4. Repeat validation for soil loss (Elliott's data and Ciesioilka).
5. Feedback of soil loss and heavy grazing on infiltration.
6. Feedback of fire frequency on weed growth and hence pasture production.
7. Supplementation and LWG/ha expressed in $ terms.
8. Seasonal liveweight gain model.
9. Evaluate alternative forecast schemes.

12. Figures

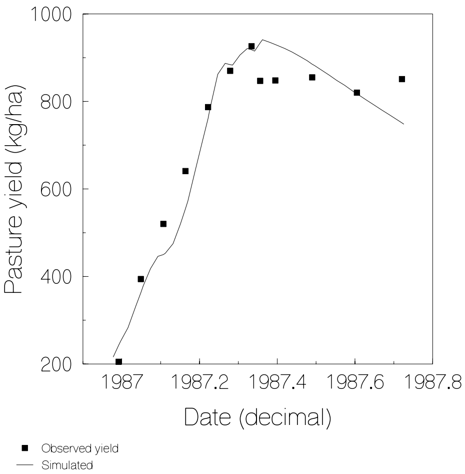

Figure 1a: *Simulation and observations of pasture yield for a woodland native pasture exclosure at Springmont, NE Queensland (data collected by L Punter and R Hendricksen).*

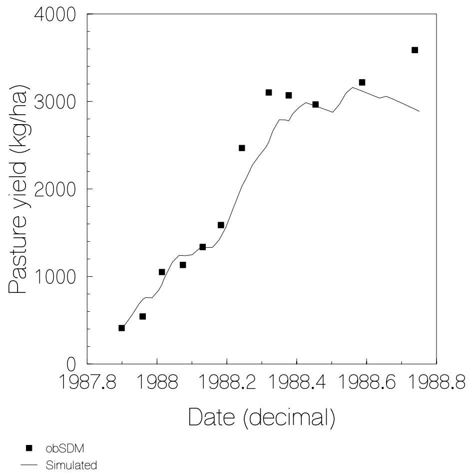

Figure 1c: *Simulation and observations of pasture yield for a cleared native pasture exclosure at Lansdown, NE Queensland (data collected by M McCaskill and R Rebgetz).*

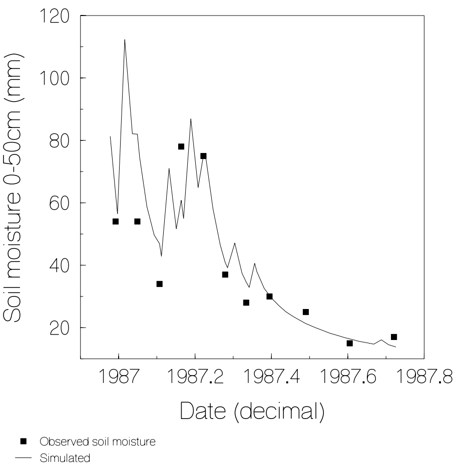

Figure 1b: *Simulation and observations of soil water, 0-50cm depth at Springmont.*

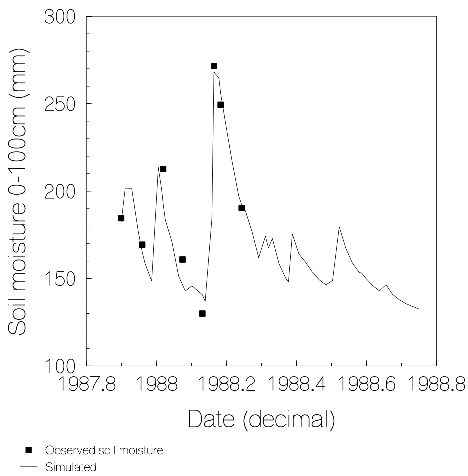

Figure 1d: *Simulation and observations of soil water, 0-100cm depth at Lansdown.*

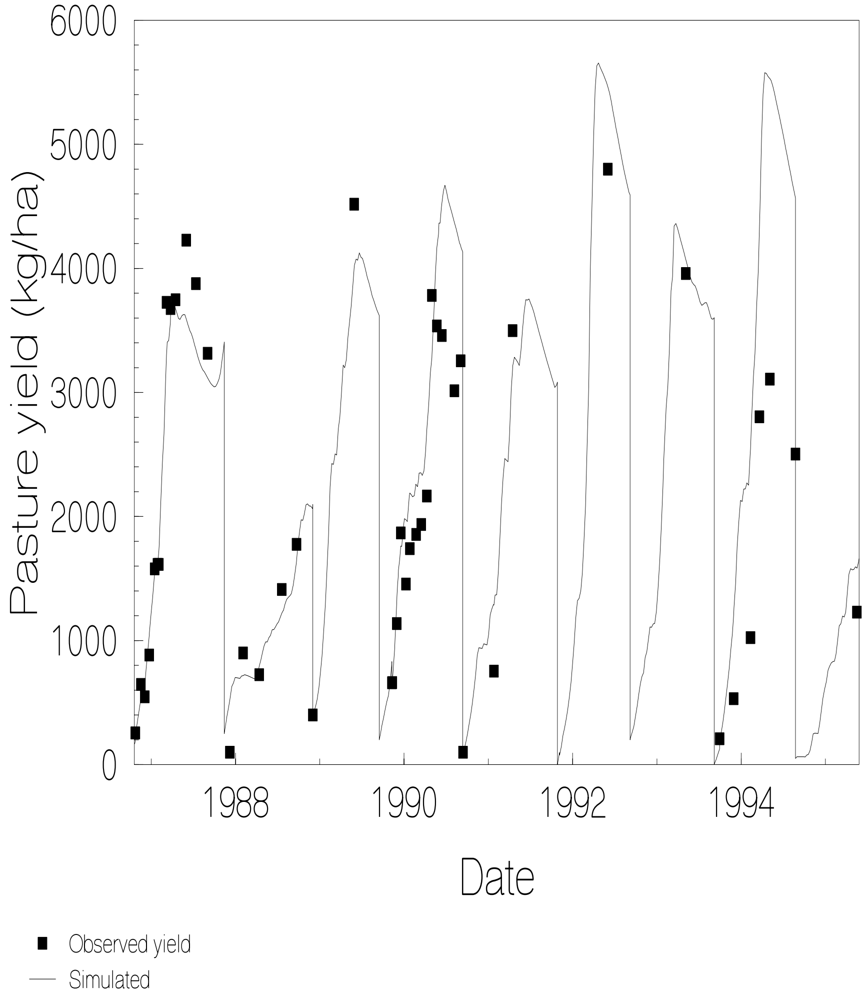

Figure 2: *Simulation of plant yield for a black speargrass exclosure at Brian Pastures Research Station, Gayndah. Pasture was burnt each year from 1986 to 1995 (data collected by K. Day, D. Orr, J. Willcocks, L. Johanson, M. Philp, and G. McKeon).*

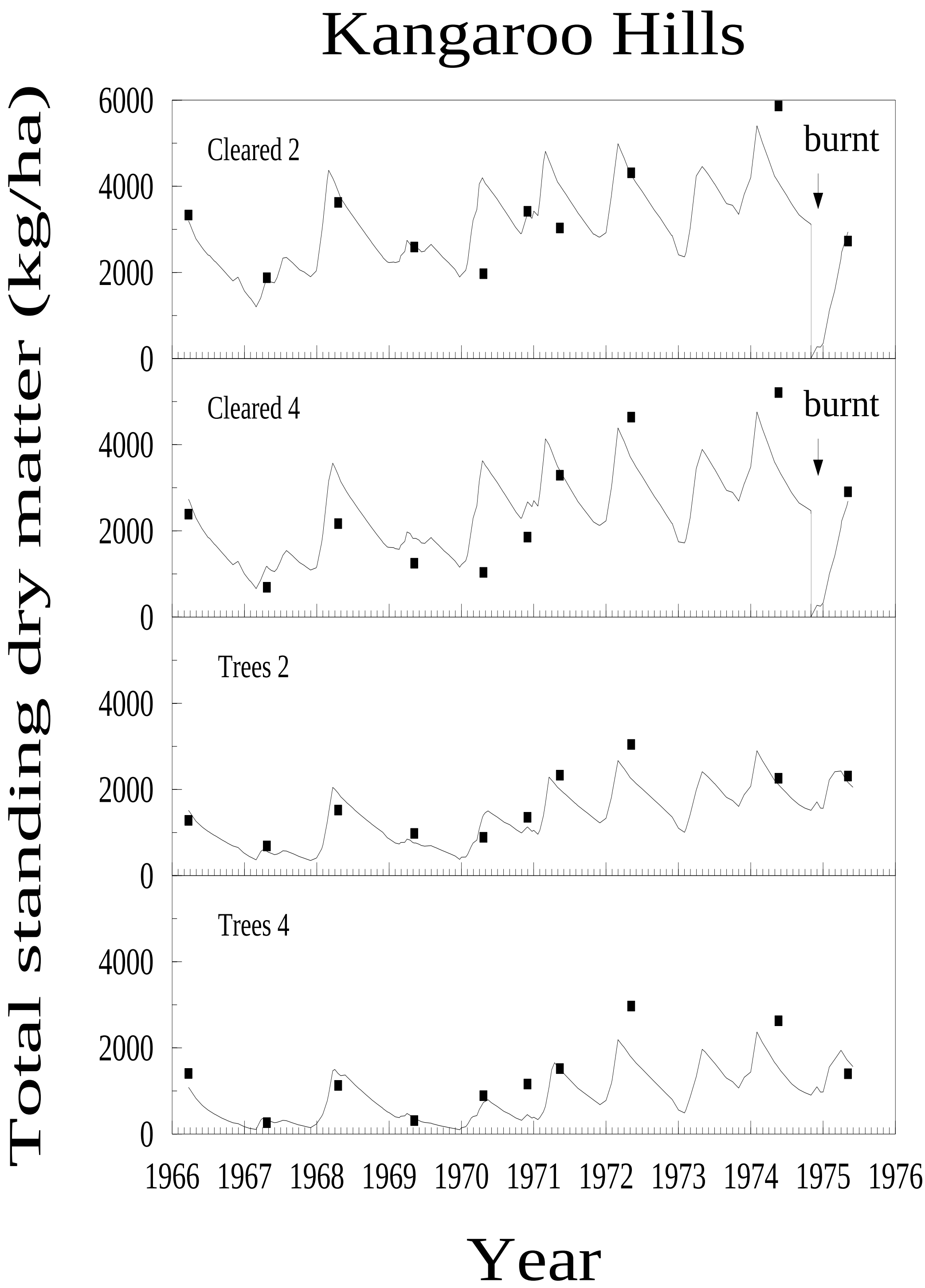

Figure 3 *: Simulated (-) and observed (■) total standing dry matter for Kangaroo Hills: (a) Cleared 2, trees killed and 0.21 head/ha; (b) Cleared 4, trees killed and 0.42 head/ha; (c) Trees 2, trees not killed and 0.21 head/ha; and (d) Trees 4, trees not killed and 0.42 head/ha.*

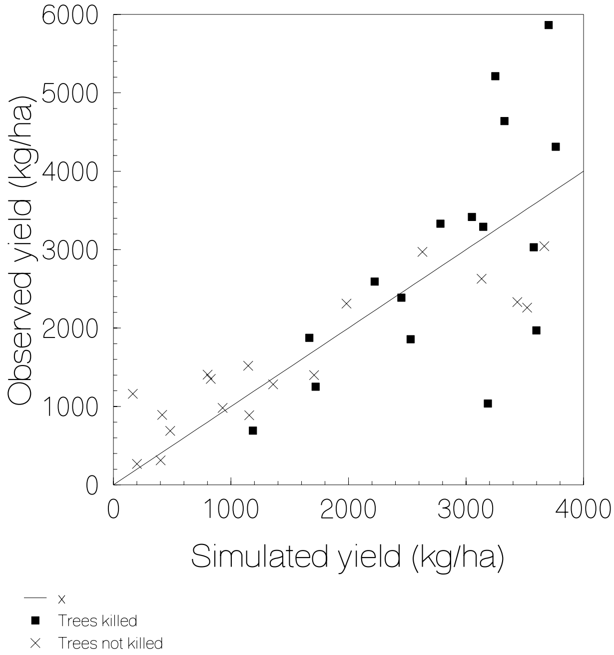

Figure 4: *Comparison of simulated pasture standing dry matter and independent observations for Kangaroo Hills (x trees not killed, ■ trees killed). Line is 1:1.*

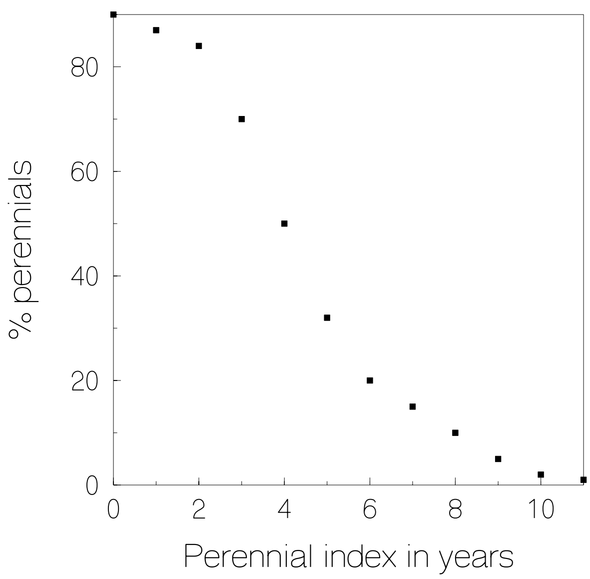

Figure 5: *The time course in perennial composition of pasture (%) with continued heavy utilisation (after Ash et al. 1996).*

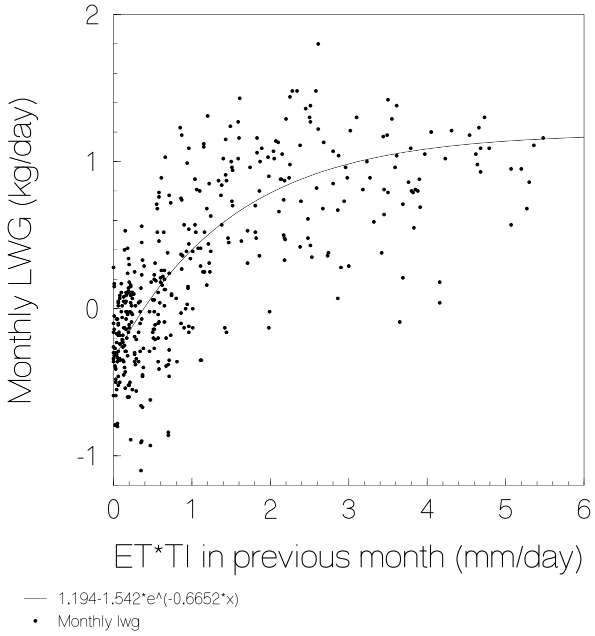

Figure 6a: *The relationship between observed monthly liveweight gain at Kangaroo Hills and simulated evapotranspiration* temperature-index (ET*TI) in previous month.*

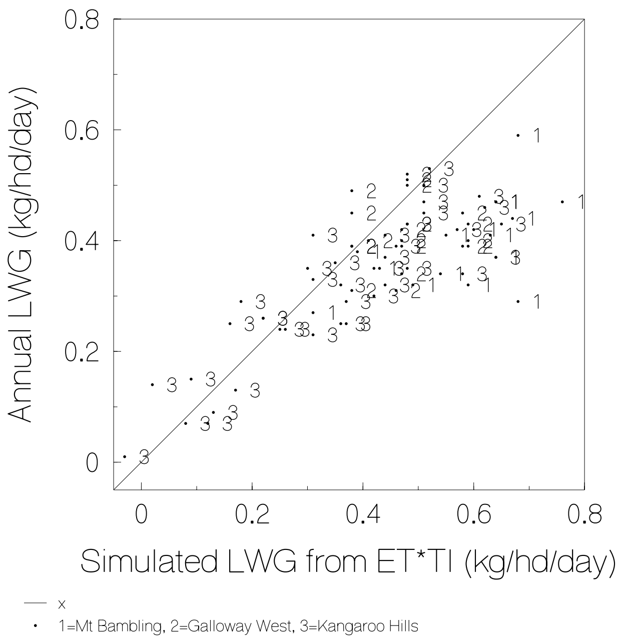

Figure 6b: *Comparison of observed annual LWG from Mt Bambling, Galloway Plains and Kangaroo Hills with predicted values calculated using the monthly LWG $_{ET}$ model.*

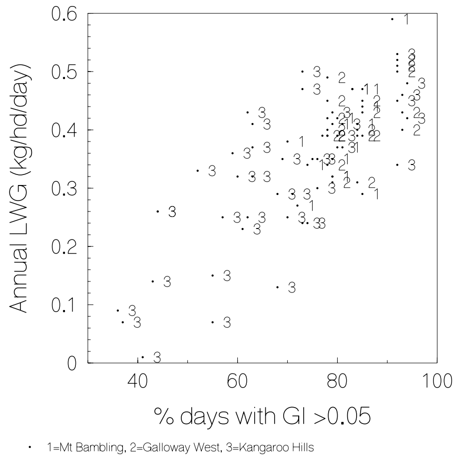

Figure 7a: *Comparison of annual LWG (kg/hd) and the percentage of days with the growth index ≥ 0.05 (%gidays) for three locations in the black spear zone (1=Mt Bamling, 2=Galloway West, and 3=Kangaroo Hills).*

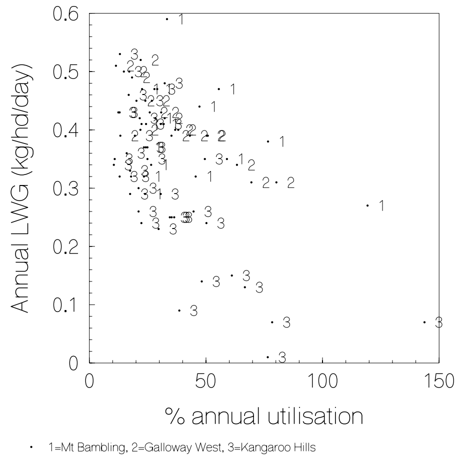

Figure 7b: *Comparison of annual LWG (kg/hd) and the percentage of pasture grown that is consumed (%utilisation).*

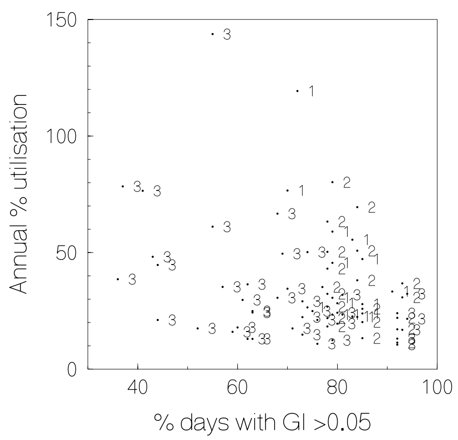

Figure 7c: *Comparison of %gidays and %utilisation for three locations in the black spear zone (1=Mt Bamling, 2=Galloway West, and 3=Kangaroo Hills).*

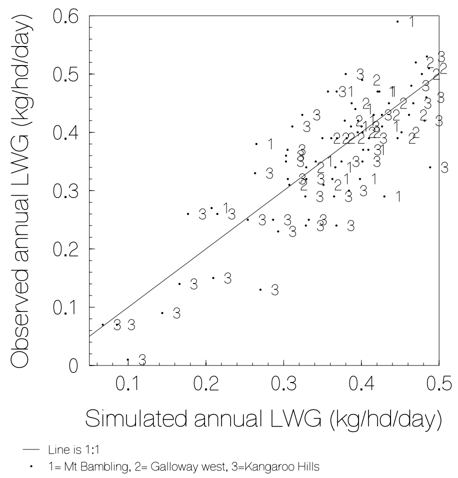

Figure 7d: *Comparison of observed and simulated annual LWG the using multiple regression model: LWG=0.013 + 0.00535 ∗%giday - 0.00016 ∗ %utilisation.*

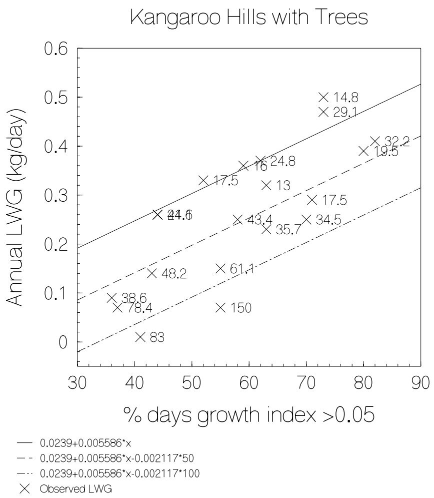

Figure 8a: *Relationship between annual LWG (kg/hd) and the percentage of days with the growth index ≥ 0.05 (%gidays) for Kangaroo Hills, trees not killed and two stocking rates. The effect of different utilisation levels (0, 50, 100%) on simulated LWG are shown. Calculated utilisation (%) are shown for each observation.*

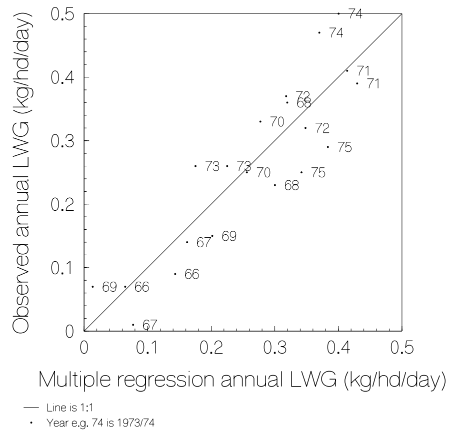

Figure 8b: *Comparison of observed annual LWG (kg/hd) and simulated LWG (74 is the observation for 1973-74).*

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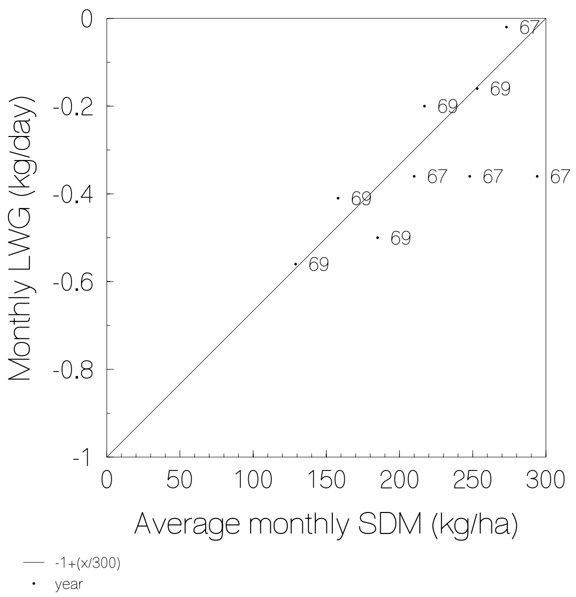

Figure 9: *The relationship between monthly liveweight loss (kg/day) and average simulated standing dry matter for Kangaroo Hills (trees not killed), at two stocking rates for conditions with less than 10% green dry matter.*

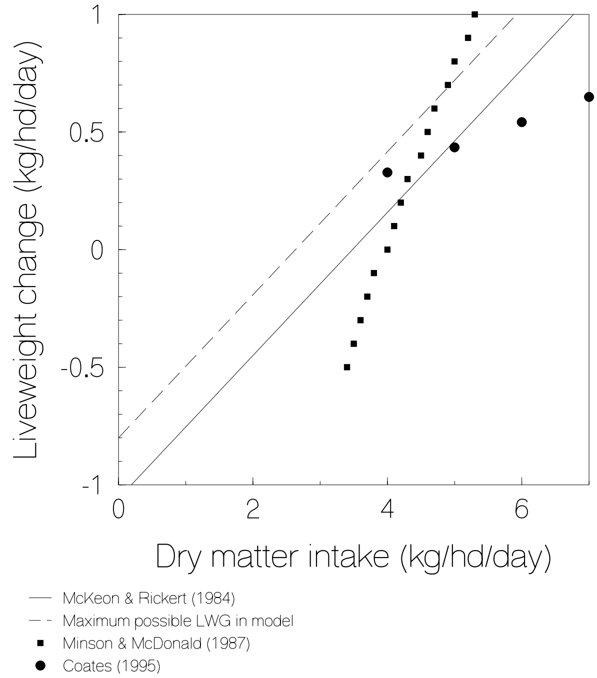

Figure 10: *The relationship between dry matter intake and liveweight gain from different sources:*

- ▪ *Minson and McDonald (1987);*
- ––– *McKeon and Rickert (1984) derived from Siebert and Hunter (1977);*
- ● *Coates (1995); and*
- \- - - *relationship used to limit liveweight in the model.*

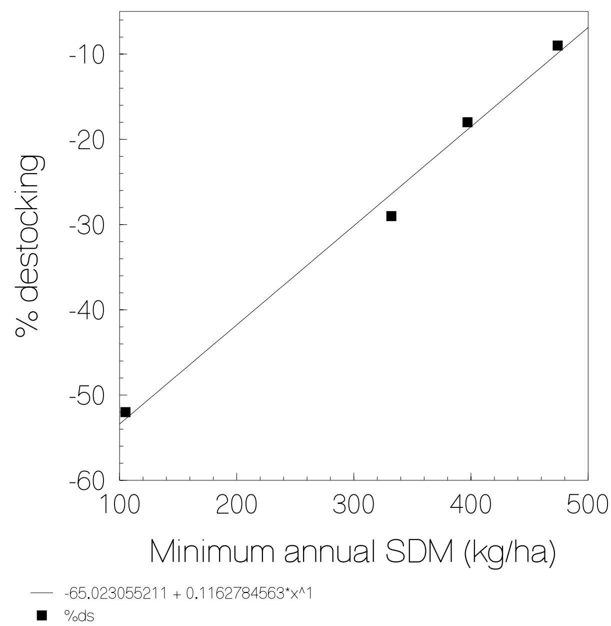

Figure 11: *The relationship between simulated standing dry matter (SDM) and % destocking in four drought years between 1982 and 1988 for a property in the Charters Towers region (data made available by A. Ash).*

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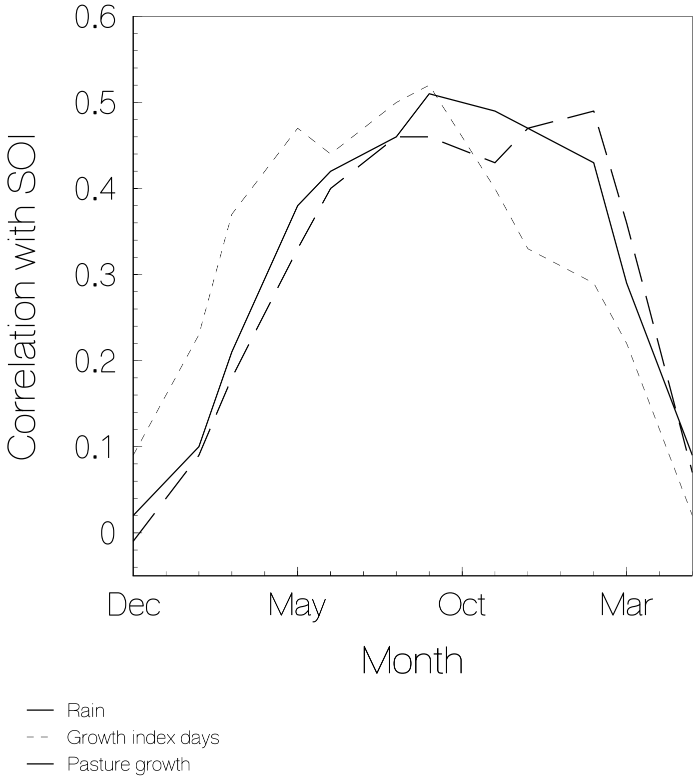

Figure 12: *The correlation between the SOI for different 3 monthly periods and variables summed for the 12 months June-May:*

— *rainfall*
\- - *% growth index days≥ 0.05*
— *annual pasture growth.*

The correlation is plotted against the first month of the SOI period.

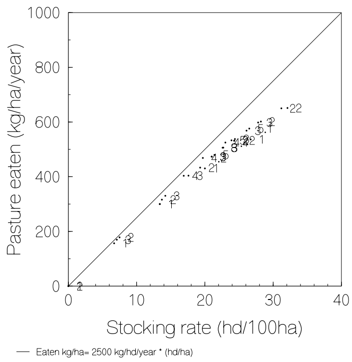

Figure 13A: *Relationship between stocking rate (head per 100ha) and average pasture eaten (kg/ha/year) for all strategies. The stocking rate is for 300 kgLW steers.*

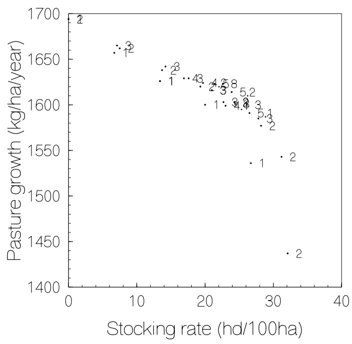

Figure 13B: *Relationship between stocking rate (head per 100ha) and average annual pasture growth (kg/ha/yr). The stocking rate is for 300kgLW steers.*

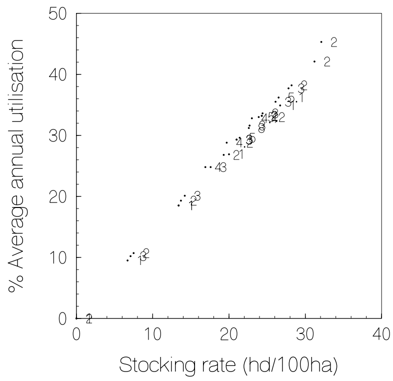

Figure 13C: *Relationship between % average annual utilisation and stocking rate (head per 100ha) for all strategies. The stocking rate is for 300 kg LW steers.*

1=*constant*, 2=*reactive*, 3=*perfect knowledge*, 4=*SOI forecast*,5=*reactive & perfect SOI*
4.0 50% reduced in stocking rate in El Niño years, 4.1 50% increased stocking rate in La Niña years

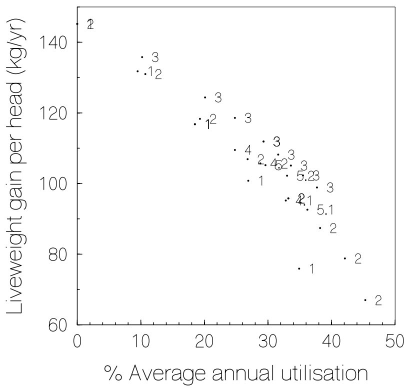

Figure 13D: *Relationship between liveweight gain per head (LWG kg/hd/yr) and average annual utilisation for all strategies.*

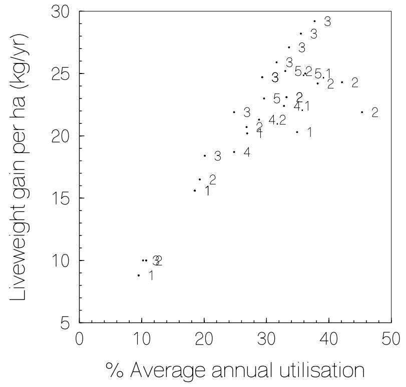

Figure 13E: *Relationship between liveweight gain per ha (LW kg/ha/yr) and average annual utilisation for all strategies.*

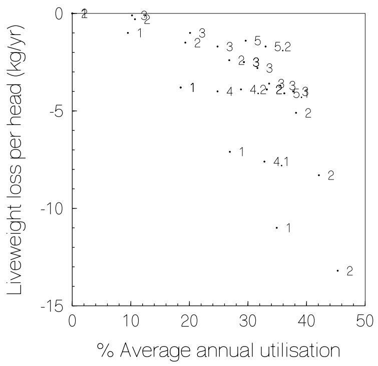

Figure 13F: *Relationship between average liveweight loss (kg/head/year) and average annual utilisation for all strategies.*

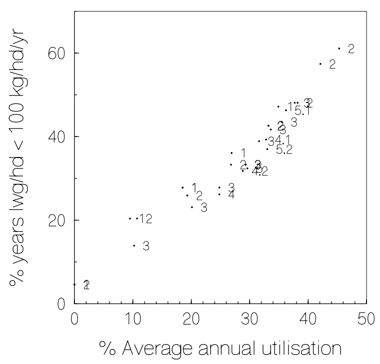

Figure 13G: *Relationship between % of year in which liveweight gain per hd was less than 100kg/yr, and average annual utilisation for all strategies.*

1=*constant*, 2=*reactive*, 3=*perfect knowledge*, 4=*SOI forecast*,5=*reactive & perfect SOI*
4.0 50% reduced in stocking rate in El Niño years, 4.1 50% increased stocking rate in La Niña years

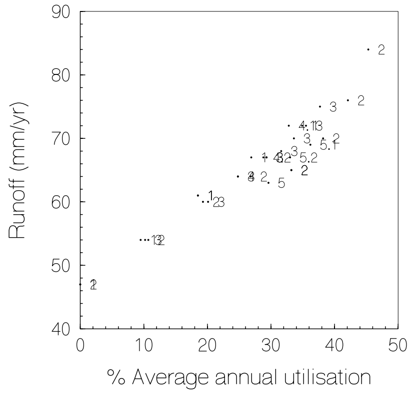

Figure 13H: *Relationship between average run-off (mm/year) and average utilisation for all strategies.*

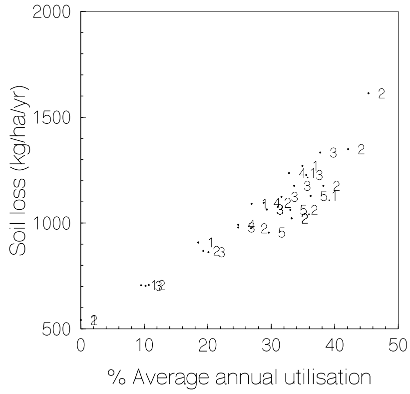

Figure 13I: *Relationship between average soil loss (kg/ha/year) and average utilisation for all strategies.*

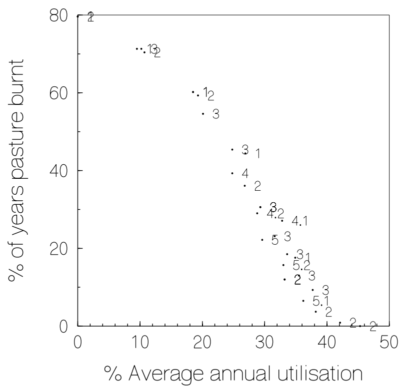

Figure 13J: *Relationship between % years in which pasture was burnt and average annual utilisation for all strategies.*

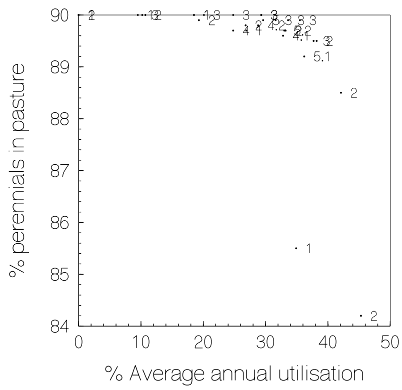

Figure 13K: *Relationship between average % perennial composition of pasture and average annual utilisation for all strategies.*

1=*constant*, 2=*reactive*, 3=*perfect knowledge*, 4=*SOI forecast*,5=*reactive & perfect SOI*
4.0 50% reduced in stocking rate in El Niño years, 4.1 50% increased stocking rate in La Niña years

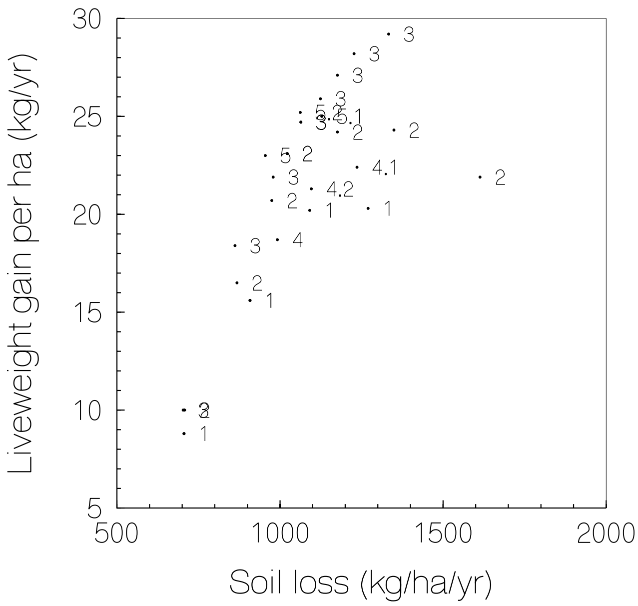

***Figure 13L:** Relationship between average liveweight gain per ha (kg/yr) and average soil loss (kg/ha/year) for all strategies.*

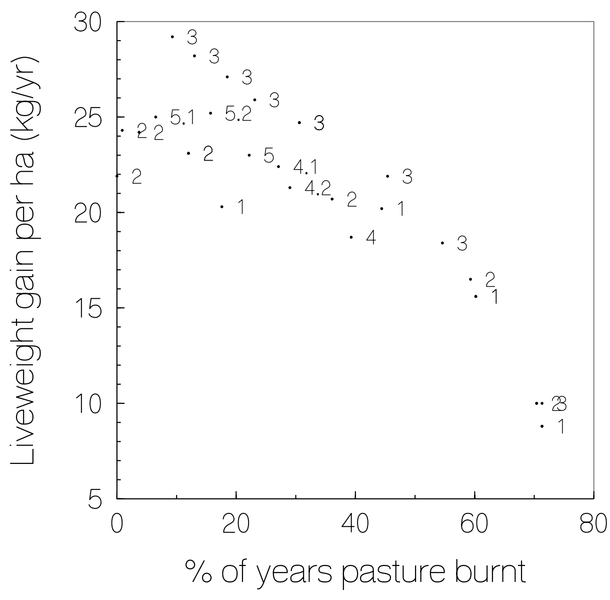

***Figure 13M:** Relationship between average liveweight gain per ha (kg/yr) and % of years in which pasture was burnt.*

1=*constant*, 2=*reactive*, 3=*perfect knowledge*, 4=*SOI forecast*,5=*reactive & perfect SOI*
4.0 50% reduced in stocking rate in El Niño years, 4.1 50% increased stocking rate in La Niña years