final report

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Total Resource Management – Incorporating Optimisation Into the SGS Pasture Model

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TOTAL RESOURCE MANAGEMENT – INCORPORATING OPTIMISATION INTO THE SGS PASTURE MODEL

Introduction

The objectives of this project centred around exploring the potential of applying differential evolution (DE) techniques with the SGS Pasture Model (the Model) both for biophysical parameter estimation and also management optimisation. We have approached the project as a *proof of concept* which has involved making various simplifications. Nevertheless, the results are interesting, and we feel that the analysis demonstrates that there could be much to be gained from developing these concepts further.

In this report, each milestone of the contract will be taken in turn and then an overall assessment of the project will be made. We do not give specific details on the underlying DE methodology, although a brief outline can be found in the conference paper (Johnson *et al.*, 2002) that has been presented as a direct result of this project. The paper is appended to this report.

During the SGS Project one of us (IJR) has worked extensively with the SGS National Experiment (NE) – indeed, the Model was developed as part of this project. As a result of that work, it was concluded that the data collected by the Tamworth team of Greg Lodge and Sean Murphy was of a particularly high quality and ideally suited to the present analysis.

The SGS Pasture Model

Before proceeding with the optimisation analysis, a brief background to the model is presented. The principal components of the model are:

- Water dynamics: soil water infiltration and through drainage, runoff (surface and sub-surface), transpiration, evaporation (canopy, litter, soil).
- Pasture growth: carbon and nutrient dynamics in response to light, temperature and soil nutrient status. Multiple species can be incorporated. Digestibility and metabolisable energy (ME) content are calculated from the N status.
- Nutrient dynamics (N, P, K, S): plant utilization, organic matter turnover (litter and dead roots), inorganic nutrient leaching, atmospheric N losses.
- Animal growth: ME based model of growth including pregnancy and lactation, and lamb growth.
- Management: the options for grazing management are set-stocked (stock permanently on the paddock), rotational grazing (stock periodically moved between paddocks), or variable sheep numbers. Options are also available for fertilizer and irrigation.

The model has an intuitive Windows interface for easy model exploration and parameterisation. Simulation results can be exported to an Excel file for further analysis. The model accounts for mass balance of all water and nutrients in the system. At runtime, the model displays user data along with the simulation for easy comparison between the two.

The Model is hierarchical in structure, in that the whole pasture system is modelled in terms of the component processes, such as plant growth, soil water balance and so on. (For a further discussion of hierarchical models see, for example, Thornley and Johnson, 2000.) A crucial aspect of this type of model structure, and one that applies to the biophysical system, is that while we can think of the individual components of the system, their behaviour is inter-connected. For example, in the pasture system, the soil water balance and pasture dynamics are not independent, as the latter affects both how much water gets into the profile and how much is taken out. In turn, pasture management affects pasture dynamics and so also affects the water balance. A central aim with this model has been to explore the behaviour of the system and to analyse the data from the SGS experiment in terms of these interactions.

Milestone 1: Data analysis and parameter estimation

Background

The aim of this part of the project was to use DE methods to estimate the soil physical parameters in the Model. The standard approach is to make direct measurements of these parameters (such as saturated hydraulic conductivity), run the model with these parameters and then compare the measurements of soil water content with model predictions. However, measuring soil physical parameters can be difficult, time consuming, and may be subject to considerable error. The strategy we have used here is to use the measurements of soil water content in the profile, and through time, to back-calculate the corresponding soil physical parameters. To be effective, this method has a number of requirements:

1. The measurements of soil water content must be accurate. This requires careful calibration of the measuring device, which is generally a neutron moisture meter (NMM). Such calibration can be difficult, and modelling can highlight limitations in experimental measurements.

2. Other components of the model must be working well, in particular estimates of evapotranspiration and runoff. If these are inaccurate then either too much or too little water will be getting into the soil and the optimisation technique will be attempting to fit the soil physical parameters to compensate for errors in other parts of the model.

3. Climatic inputs, particularly rainfall, must be accurate.

As a corollary to these points, if a model does not give good agreement between the measured and predicted values for soil water content, it may not indicate that there are specific problems with the soil water infiltration component of the model.

Model development and analysis

The analysis is described in the appended paper (Johnson *et al.*, 2002) that was presented at the IASTED Applied Simulation and Modelling conference. The paper was well received and stimulated a considerable amount of discussion. Further discussion of this component of the project is restricted to conclusions and recommendations.

Conclusions and recommendations

The approach worked well in estimating the soil physical parameters, and gives us confidence that the general approach is sound. However, we do recognise the importance of the observed data reflecting the full range of behaviour over which the fitted parameters are applicable. The key parameters here are the saturated hydraulic conductivity, the saturated water content, drainage point (the water content to which the profile will drain) and the conductance parameter that defines the decline in flux of water as the soil dries down (see the equation on p. 275 in the paper). The interaction between these parameters defines the flux of water over the entire range of water content between saturation and drainage. Consequently, it is important that the observed data that are used to estimate the parameters cover this range, otherwise confounding fits may be obtained that are only applicable in the range of data observations.

It is therefore recommended that the model be applied under experimental conditions where the soil is artificially wetted and allowed to dry down, during which time it is frequently monitored. The advantages of this approach are:

- It will allow the analysis to be applied over the entire range of soil water contents.
- It will isolate the soil water component of the model from other components such as evapotranspiration and runoff.

Milestone 2: Optimise pasture utilisation in response to grazing management.

Background

This part of the project has been challenging, and yet has also been very interesting. The aim was to identify appropriate stocking rates to optimise the economic return from the pasture. To address these problems, a simple cash-balance component has been incorporated in the model. This sub-model is a simplification of what happens in practice and the output should be considered accordingly. Nevertheless, it is does provide useful insight into the possible management strategies and serves to assess the potential for further development.

The general strategy is to use the model to identify what would be the optimum stocking rate for each year. This operates under the assumption that decisions are made with the benefit of knowing what the future weather conditions will be – a bit of a luxury! However, by analysing the system in this way and then studying the results we can identify risks associated with different strategies over the long term. Also, strategies that are analysed that *don't* have prior knowledge of the weather can be compared to those that do to see how close they come to optimum. Risk analysis strategies are discussed later (Milestone 5). A further value of the present approach is to see if the DE model can actually find sensible solutions – if it works for the problem defined here then it gives us confidence that it can be used to analyse more complex scenarios. The model also considers efficient strategies for supplementary feed, and these parameters are included in the optimisation analysis.

Throughout this analysis, we do not distinguish between supplementary feed as a source of protein or fibre. The model only looks at the ME requirement of the animals and applies supplementary feed in relation to ME. Clearly, there is potential for more detail in this regard but, for the present work, the approach is sufficient.

The model

The model is a simple crossbred lamb production system. This is notionally bought-in Poll Dorset rams (cost of these assumed fixed) over bought-in Border Leicester x Merino crossbred ewes. The number of young ewes bought in each year is optimised, as a way of controlling stocking density for the coming year. Prices were assumed as follows:

Cost of young ewe	\$61
Sell price of cull ewe	\$1.8 x 0.45 per kg live-weight
Sell price of lamb	\$3 x 0.45 per kg live-weight
Sell price of fleece (lamb or ewe)	\$8

where the factor 0.45 converts live-weight to carcass weight.

The following assumptions were adopted:

- Twenty percent of ewes were assumed to be culled for age in each year, with control of flock size being exercised through ewe purchase decisions alone. A more developed system will handle this area more correctly, but effects on outcome are expected to be similar.
- Twin rate is taken to be 50%.
- Lamb and ewe mortality is ignored.
- Ewe purchase occurs at the same time as weaning and selling of lambs, so that the model only adjusts stocking rate once a year

Prices are obviously subject to considerable variation, depending on the state of the market and so on. However, in the exploratory analysis presented here such variation is not considered. The results must therefore be viewed with this in mind but, nevertheless, they do show sensible patterns.

Note that we make no account for fixed costs, infra-structure costs or inflation. The results and discussion should take this into account, although we do anticipate that the trends and patterns that are observed will be relatively consistent with a more realistic economic treatment.

As well as the prices associated with buying and selling animals, we have also considered the cost of supplementary feed. This is an integral component of the model and has a substantial influence on the optimisation scheme. For low stocking rates, supplementary feed inputs will be low but so will return through selling animals. Conversely, for high stocking rates, supplementary feed inputs will be high (or animals will die) and so, while return from selling animals will be high, the net result of supplementary feed costs and return on animal sales may be low.

The feeding strategy in the Model is defined with two parameters, as follows:

- First, the ME requirement of the grazing animal is calculated. This includes growth, maintenance, pregnancy and lactation as appropriate.
- Then ME pasture intake is calculated.
- If this is below a prescribed threshold then intake is supplemented so that total ME intake reaches a second prescribed value.

For example, suppose the pasture ME intake below which supplementary feed is supplied is 75% of requirement and the value to which the animals are subsequently fed is 95% of requirement. In this case, if pasture intake supplies greater than 75% of requirement, no supplementary feed is supplied. However, if pasture intake supplies less than 75% of requirement then feed is supplied to the extent that total intake from pasture and supplementary feed is 95% of requirement.

The supplementary feed parameters have been derived as constant for the entire duration of the simulation, but separately for each treatment. They are denoted as p1 and p2, where

- p1 is the % ME intake requirement below which to implement supplementary feed;
- p2 is the % ME intake requirement to feed to.

The parameters to optimise are:

- Annual ewe stocking density;
- Supplementary feeding parameters.

Thus, for a simulation over N years, there are N+2 parameters.

Since initial parameters for soil water content and pasture dry weight can have a substantial bearing on the subsequent simulation, all simulations were run for one year prior to the optimisation analysis.

Site simulation

All simulations are for a phalaris pasture at Barraba, which is the Tamworth SGS site. The pasture species are phalaris, sub-clover, annual ryegrass and red grass. All simulations are for the period 1975 to 1985 which includes a mixture of rainfall years and is intended to allow analysis of variable climatic conditions. The annual rainfall for this period is show in Fig. 1:

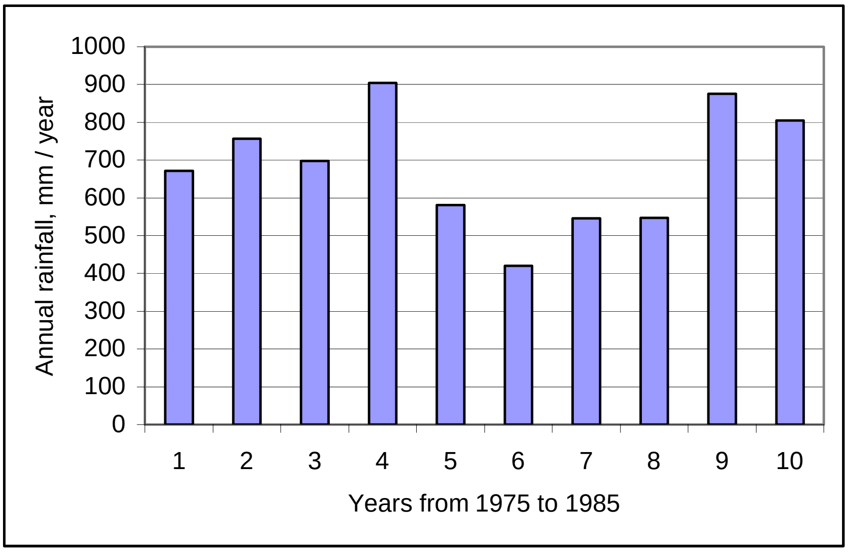


Figure 1: Annual rainfall for the 10 year period of the simulations.

Care must be taken when using annual rainfall alone to assess the impact of rainfall on pasture production. For example, Murphy *et al*. (2002) have shown, using the model, that it is important to consider seasonal patterns rather than annual patterns alone.

The model was run for three supplementary feed costs: $200, $400, $800 per tonne, denoted by F200, F400, F800 respectively. While this does represent an extreme range, and costs will normally vary, it does serve to give an indication of the impact of varying supplementary feed costs.

The results of the optimisation for stock density and annual profit are shown in Figs 2, 3

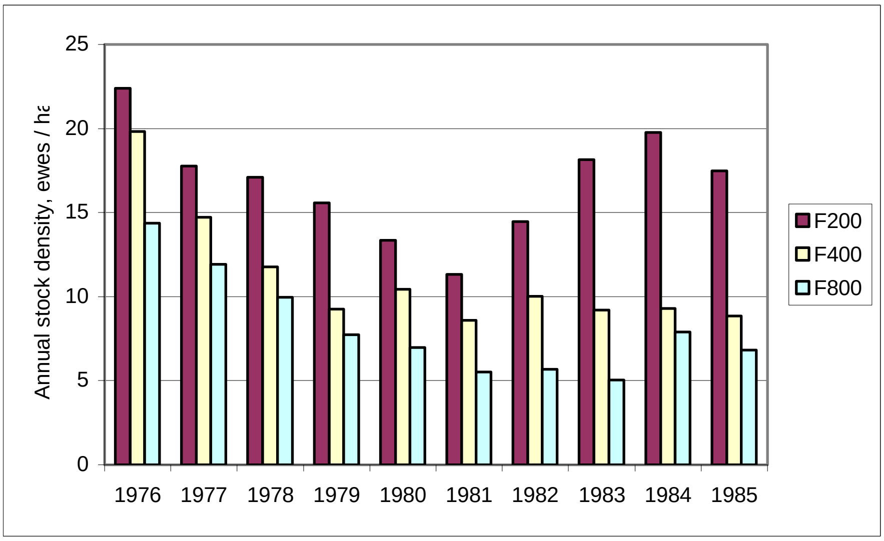


Figure 2: Annual stock density for the three different supplementary feed costs being considered.

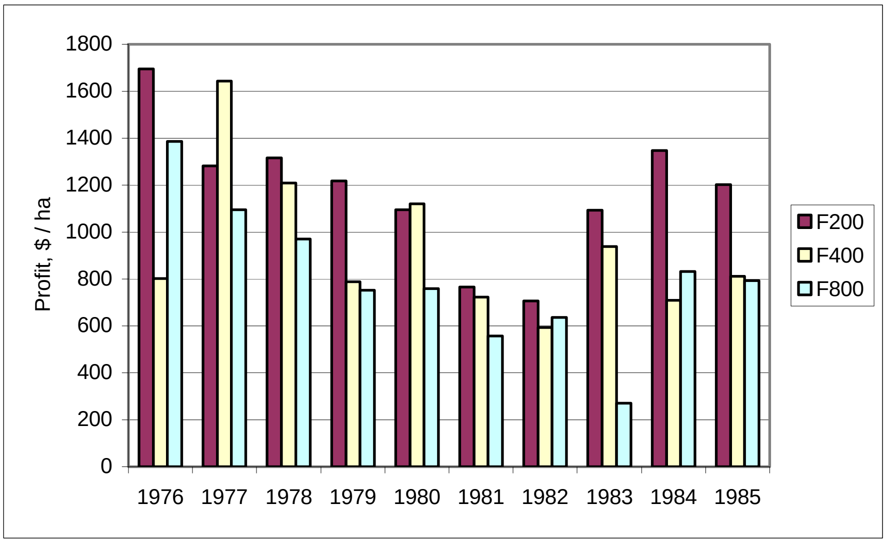


Figure 3: Annual profit for the three different supplementary feed costs being considered, corresponding to Fig. 2.

As well as calculating the optimum stocking rates, the supplementary feed parameters were also derived and these are given in Table 1:

Feed cost ($/t)	p1	p2
200	66	90
400	74	89
800	68	91

Table 1: Derived supplementary feed parameters for the range of feed costs.

Table 2 shows the mean values over the 10 year period for stock density and profit:

Feed cost ($/t)	Stock density	Profit ($/ha)
200	16.7	1172
400	11.2	934
800	8.2	805

Table 2: Mean annual stock density and profit for the range of feed costs.

Some interesting points to note are:

- The supplementary feed cost has a marked bearing on the optimum stock density.
- Although the general trend in stock density between the different treatments is similar, it does not correspond directly to annual rainfall (Fig. 1), which is presumably due to seasonal variation in rain.
- The patterns for annual profit are quite different between treatments.
- The supplementary feed parameters are quite similar over each treatment.

While we have presented the mean stocking rate for the 10 year period, we do not imply that this is an appropriate carrying capacity for all years: this is considered further in Milestone 5.

Milestone 3: Optimisation in response to fertilizer application with environmental constraints

The intention of this component of the model was to incorporate fertilizer applications to the economic model, include associated costs in the optimisation scheme and then impose environmental constraints on nutrient losses through runoff or leaching. The nutrients that are of particular concern in Australian pasture systems are arguably nitrogen and phosphorus. Nitrogen losses occur as nitrate that is lost through leaching, due to the fact that nitrate does not adsorb to the particles in the soil and so is transported freely with water movement. Phosphorus is quite different to nitrate in that it readily adsorbs to the soil particles and generally moves very slowly, if at all, through soil due to water infiltration (although movement can occur in very sandy soils). In the SGS NE, results that became available late in the experiment have indicated that phosphorus losses in runoff water were negligible. Furthermore, there was very little application of nitrogen fertilizer as sites the source of nitrogen was generally from sub-clover.

We feel, in retrospect, that the focus of this milestone is not entirely appropriate to the pasture system being considered, and have therefore identified an alternative, but related, problem to examine. The intention was always to look at sustainable land management and the issue that is arguably of most significance in the livestock pasture industry is land degradation through over grazing. When this occurs, pastures can be effectively destroyed and require re-sowing, and topsoil can be lost through runoff (although, as mentioned, this did not occur in the SGS NE). Re-sowing pastures can cost in the order of $300 / ha (with about a 75% success rate) and losses of topsoil can have a long-term detrimental effect both locally on the paddock and also on the surrounding environment.

The parameters for animal intake in relation to available pasture dry weight are those that have used in the SGS NE simulations. For animal intake in relation to available pasture, this assumes that there has to be a minimum of 400 kg/ha for intake – the potential intake curve is shown in Fig. 4, although it must be noted that actual intake may be less, depending on demand.

The common recommendation for pasture cover is to maintain a minimum of approximately 70% ground cover, which we interpret as being around 800 kg / ha. This means that management strategies must be implemented to ensure this minimum level of ground cover. Doing so will restrict available feed to the stock in the short-term, but may be beneficial in the long-term.

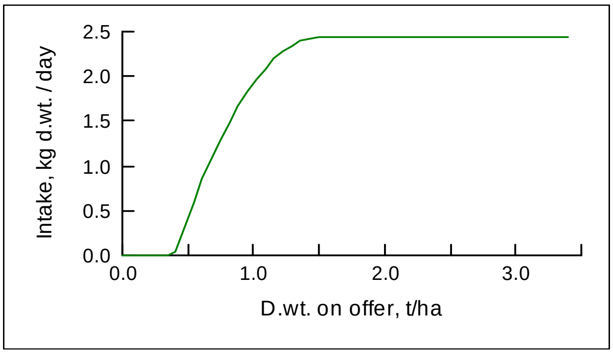


Figure 4: Potential animal (sheep) intake in relation to pasture feed on offer.

The simulations considered for Milestone 2 were therefore run again but with the residual pasture dry weight constrained to remain above 800 kg/ha which is of the required level of ground cover. The results corresponding to those presented in Milestone 2 are now shown, but with the constraint that pasture intake does not allow the pasture residual to go below 800 kg.

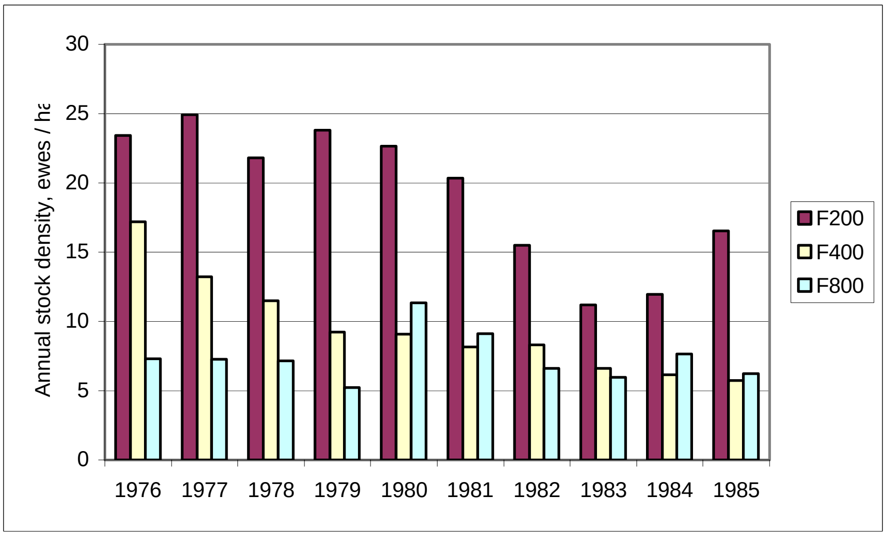


Figure 5: Annual stock density for the three different supplementary feed costs being considered.

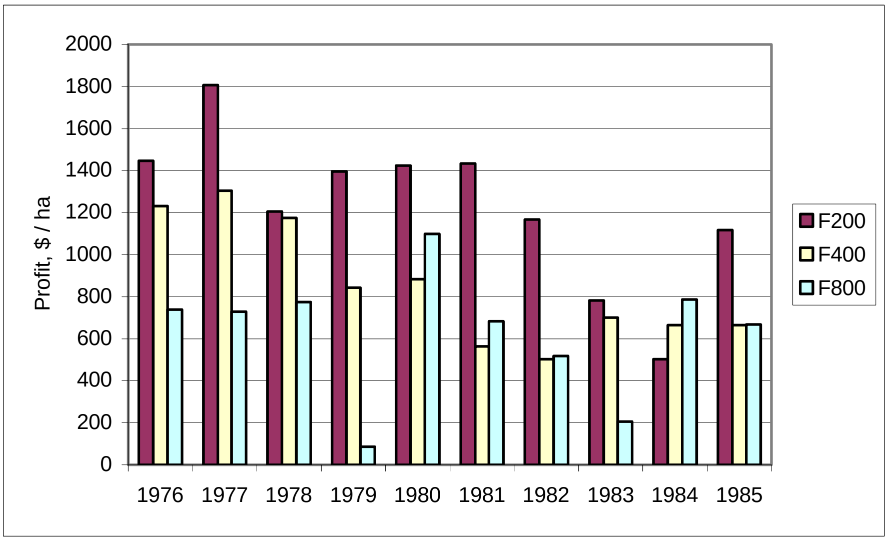


Figure 6: Annual profit for the three different supplementary feed costs being considered, corresponding to Fig. 5.

The corresponding feeding parameters are given in Table 3:

Feed cost ($/t)	p1	p2
200	77	88
400	77	95
800	70	91

Table 3: Derived supplementary feed parameters for the range of feed costs.

The mean values over the 10 year period for stock density and profit are presented in Table 4:

Feed cost ($/t)	Stock density	Profit ($/ha)
200	19.2	1228
400	9.5	853
800	7.4	629

Table 4: Derived supplementary feed parameters for the range of feed costs.

Comparing these figures with those in Table 2 where the residual pasture d.wt. was set to 400 kg / ha, it can be seen that the pasture is actually carrying more stock (19.2 vs 16.7, or 15%) and making a bit more profit (1228 vs 1172, or 4.8%) with the higher residual when supplementary feed cost is low, whereas the trend is reversed at high feed costs.

The supplementary feed parameters are quite similar across feed costs and for the low or high pasture residual, with the expected feature that supplementary feed needs to be applied a bit sooner for the low residual.

We can conclude from this preliminary analysis that there is likely to be little financial benefit from overgrazing the sward, regardless of the cost of supplementary feed, and so it should be possible to devise effective management strategies that are designed to avoid overgrazing that may well be financially attractive. Furthermore, if we incorporate the extra cost of re-sowing pasture it may well be that there is actually a financial benefit to leaving a good ground cover.

Milestone 4: Assess the potential of constrained optimisation

The simulations presented here demonstrate clearly that the DE approach that has been incorporated into the Model works effectively. The DE approach is extremely versatile and has found optimum stocking densities that appear to be consistent across the treatments considered. This is important as it confirms that the combination of the DE with the Model is effective: in fact, this could be seen as a major outcome of this *proof of concept* project.

The underlying principle of the DE approach is such that to introduce extra parameters or impose constraints is quite trivial. Only a few lines of code need to be modified. Furthermore, the approach seems to be very efficient. For example, in the present problem we were fitting 12 parameters (stocking rate for 10 years plus the two supplementary feeding parameters). If a simple search were to be imposed that allowed 10 possible values for each parameter, this would require a total of 10^{12} simulations. In the DE we typically found that the optimum was reached with less than 150 generations with a population size of 8, which corresponds to 1200 simulations. In fact, only very minor improvements were generally seen after 100 generations. An example is shown in Fig. 7 for the F200_R400 simulation described above – convergence is clear.

Perhaps the most commonly used alternative approach for economic optimisation is *Dynamic Programming* (DP): for a discussion see, for example, France and Thornley (1984). This approach involves prescribing a set of possible values for all parameters to be modified and then searching for the optimum pathway through the parameter space. One of us (IRJ) has had some experience with the method in relation to the SGS project and found it to be difficult to work with and very inflexible. Our unequivocal conclusion is that DE is far superior and has much greater potential than DP.

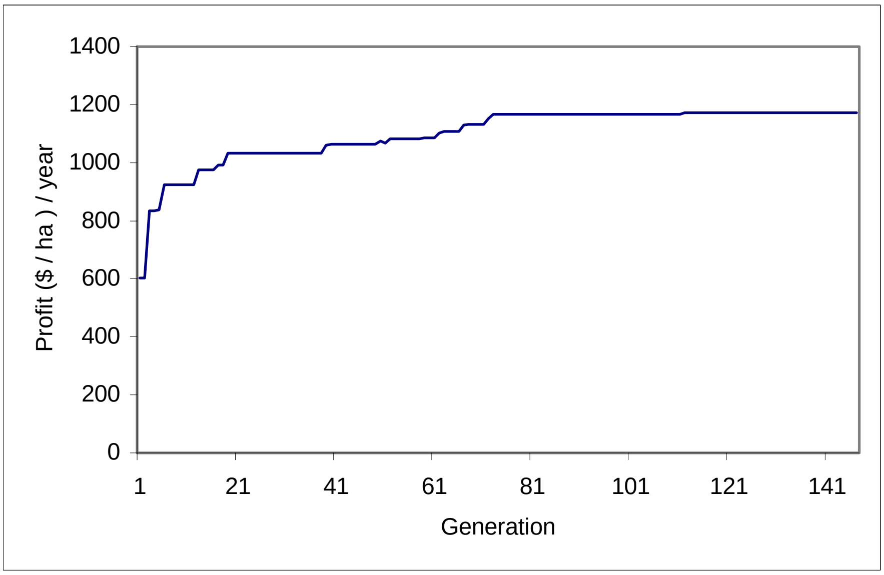


Figure 7: Asymptotic approach to the optimum solution by the DE for the F200_R400 treatment.

The constraint that was applied here is fairly simple: that is, maintaining a minimum pasture residual. However, incorporating extra constraints will incur negligible extra complexity to the model. Two obvious approaches can be adopted:

- Solutions can simply be rejected if a constraint is violated. For example, if animal liveweight falls below a prescribed percentage of normal liveweight for age.

- A substantial economic penalty can be imposed if a constraint is violated. For example, if pasture residual dry weight falls below a prescribed value then a cost for pasture re-establishment can be imposed;

- A constraint can be incorporated that cannot be violated. This is the approach that was adopted here where the animals were not allowed to graze below a specified residual so that supplementary feeding had to be implemented.

None of these methods pose any significant methodological difficulties.

We are also confident that the DE can handle relatively large numbers of parameters for optimisation. This will allow us to extend the current analysis to include more flexible economics such as variable supplementary feed costs and the option to buy and sell animals more frequently than once per year.

Milestone 5: Useful approaches to risk analysis

While the analysis presented here is based on relatively simple assumptions it does, nevertheless, give sensible results for the problems being considered. This gives us confidence that the approach can be used effectively for more realistic problems. Some of these problems are now considered.

The main risk faced by the grazing industry is drought. The obvious ways to deal with drought are to de-stock and supply supplementary feed the animals. The relative extent to which these strategies should be applied depends on factors such as the state of the market, availability and cost of feed, and requirement to maintain breeding stock. The timing of de-stocking also is crucial. Furthermore, if high stocking rates are retained then there is a significant possibility of land degradation and pasture damage. The costs of land degradation may be difficult to assess but to re-sow a pasture the associated costs are around $300 per ha, with approximately 75% success rate.

Drought must always be anticipated. In the figure below, the difference between the mean and actual annual rainfall for the SGS Barraba site is shown over a 30 year period from 1971 to 2001. While this is a relatively short period in terms of weather patterns, it is reasonable to expect droughts to occur quite regularly, but also not to last more than a few years. We must therefore study the system with this timeframe in mind, which requires planning for drought.

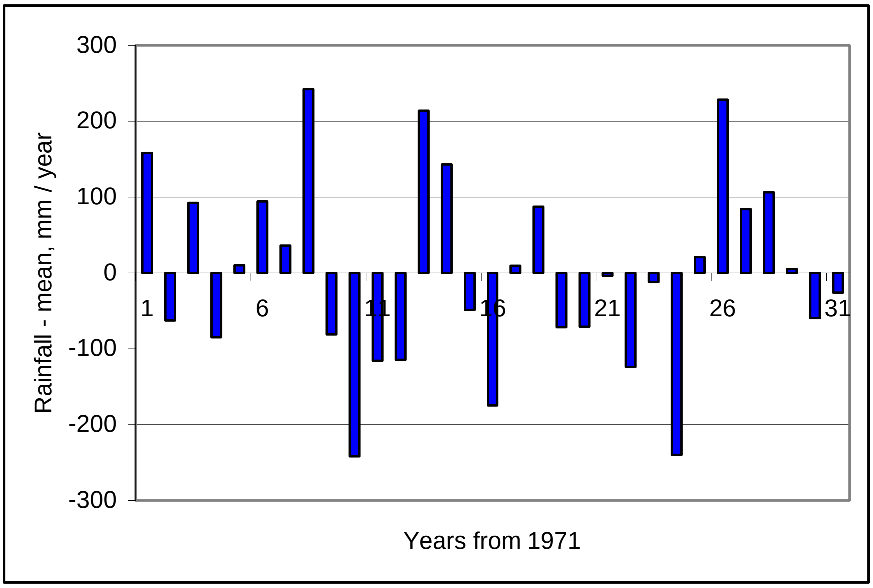


Figure 8: Rainfall variation about the mean for the period 1971 to 2001 at Barraba (Tamworth).

This illustration should only be seen as a guide. Annual rainfall in itself is not a complete indicator of drought since timing of rainfall is important (Murphy *et al.,* 2002). For example, 1998 was the wettest winter on record at this site although the rainfall for that year was only 106 mm above average.

A reasonable problem structure to address with the Model, suitably modified, is:

- Allow for on-farm fodder conservation, such as lucerne hay.
- Incorporate variable costs for purchasing fodder.
- Incorporate pasture persistence and damage due to over-grazing, and include re-sowing costs.
- Incorporate rotational grazing. This may allow rationing of pasture to the animals and also restrict over grazing to small, manageable areas.

The model could then be used to optimise economic return using historical data. Once this is done, the optimum strategy can then be analysed in terms of climate pattern. This can then be used to assess possible future strategies for grazing management.

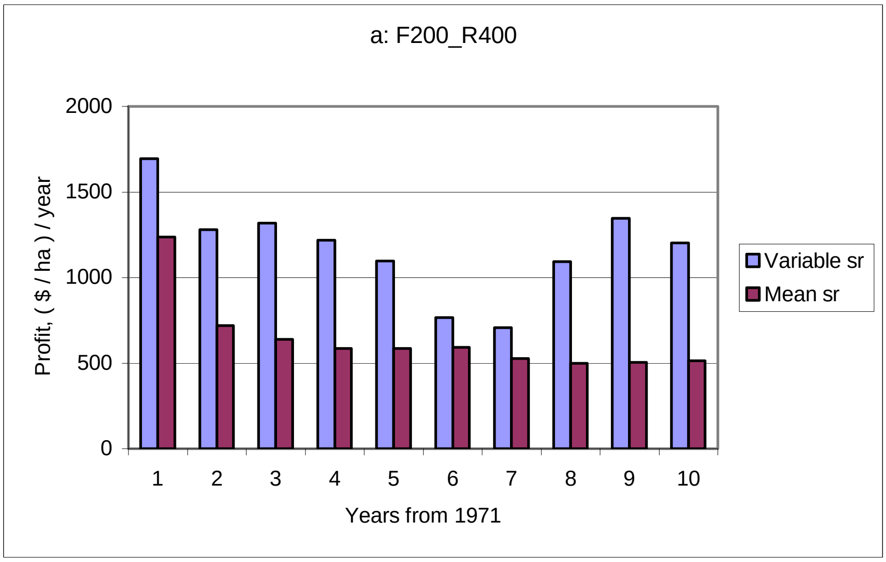
Example

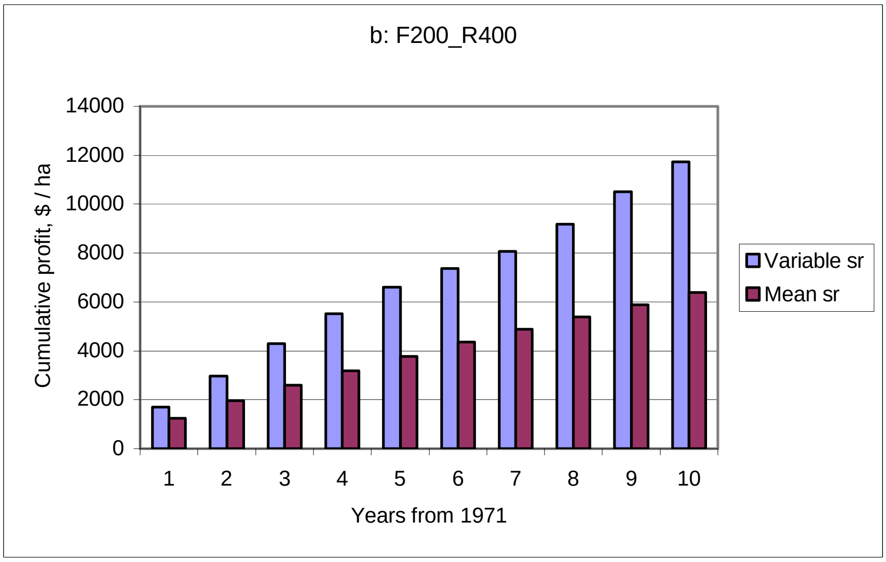
A simple example of exploring risk is now considered. It is fairly unconventional in the realms of risk analysis, but we feel that risk analysis is ripe for a bit of creative analysis! Here, the scenarios presented in Milestones 2 and 3 are repeated but with the stocking rate kept constant at the mean value for the simulation. The scenarios that are be considered for this example are where supplementary feed costs $200 and the pasture residual is either 400 or 800 kg/ha. The results can then be compared with the variable stocking rate.

Three graphs are presented:

- Annual profit.
- Cumulative profit.
- Difference between annual profit and mean annual profit.

Figures 9a, b, c and 10a, b, c show the results for the 400 and 800 kg / ha residual respectively (using the feeding parameters that were derived as optimum for each treatment).





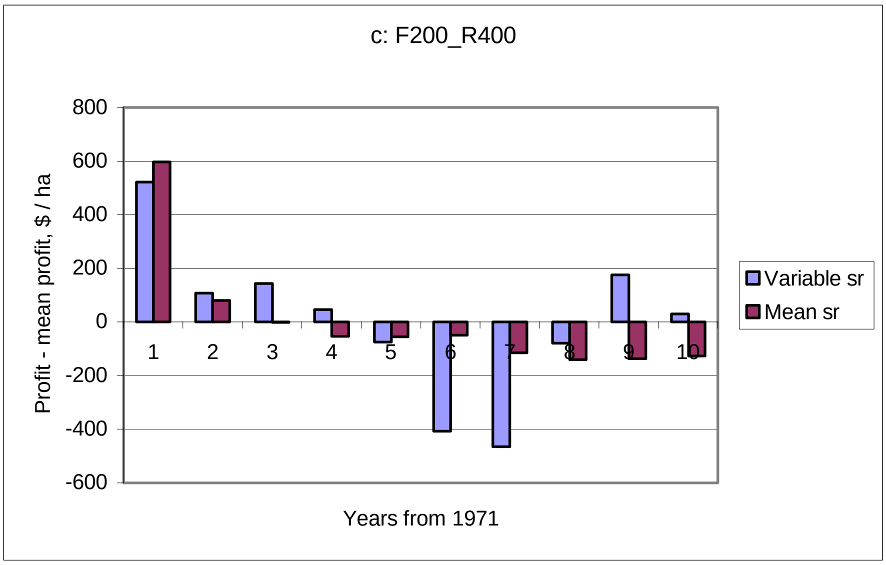
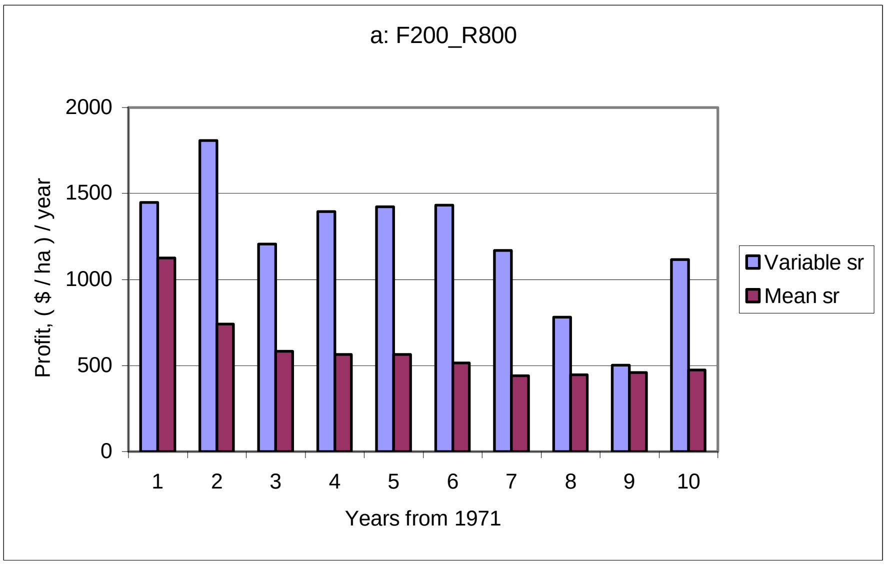
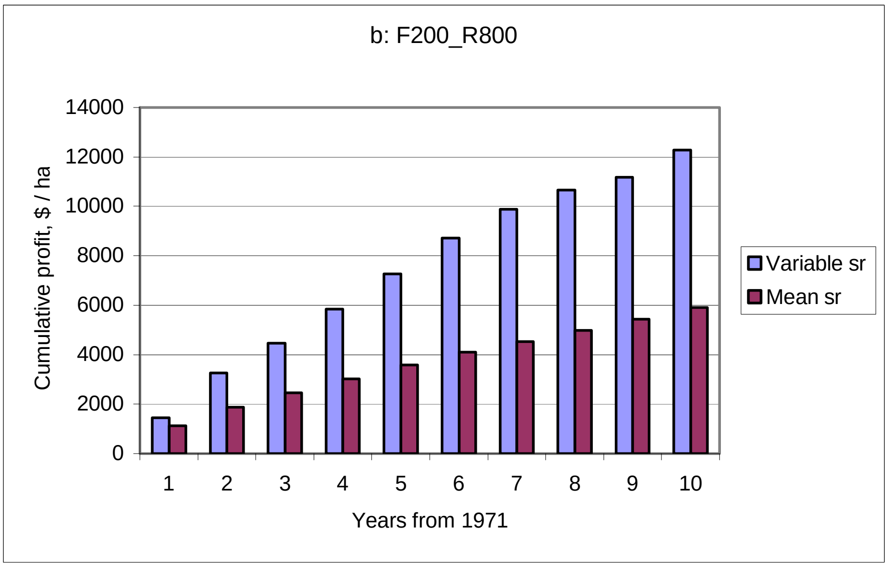


Figure 9: Comparison between variable optimum and mean of optimum stocking rate for the F200_R400 treatment. The figures are, respectively, annual profit, cumulative profit and difference between annual and mean annual profit.





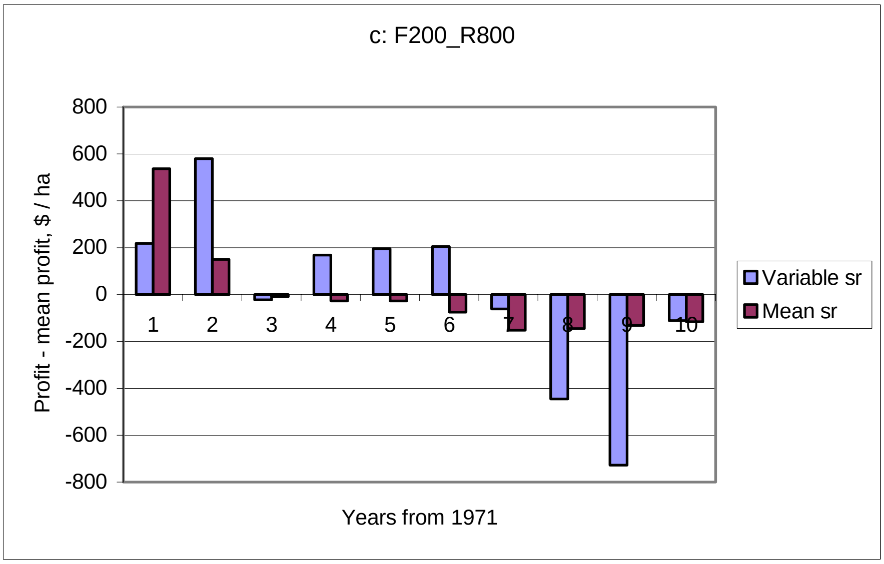


Figure 10: Comparison between variable optimum and mean of optimum stocking rate for the F200_R800 treatment, corresponding to Fig. 9.

These results are quite dramatic. The indicate clearly that attempting to support the mean stocking rate is much less viable than having stocking rate adapt to environmental conditions. However, variation about the mean profit is also more variable indicating that with the variable stocking rate comes substantial fluctuations in income. This strengthens the notion that pasture management must work on the long-term time scale.

We have purposely chosen the low feed cost option for this analysis as the mean profits were similar for the two residuals. Similar analyses are possible for the other treatments.

An alternative way of comparing the set stocked with variable optimum stocked results is to plot the mean annual profit for a range of long-term set stocked values. This is shown in Fig. 11, but now for the F200_R400 and F400_R400, so that we are now comparing the effect of changing feed costs rather than pasture residual. Also shown is the actual profit (broken line) for the optimum stocking rate: note that in this graph, annual values are averaged over the 10 years of the simulation.

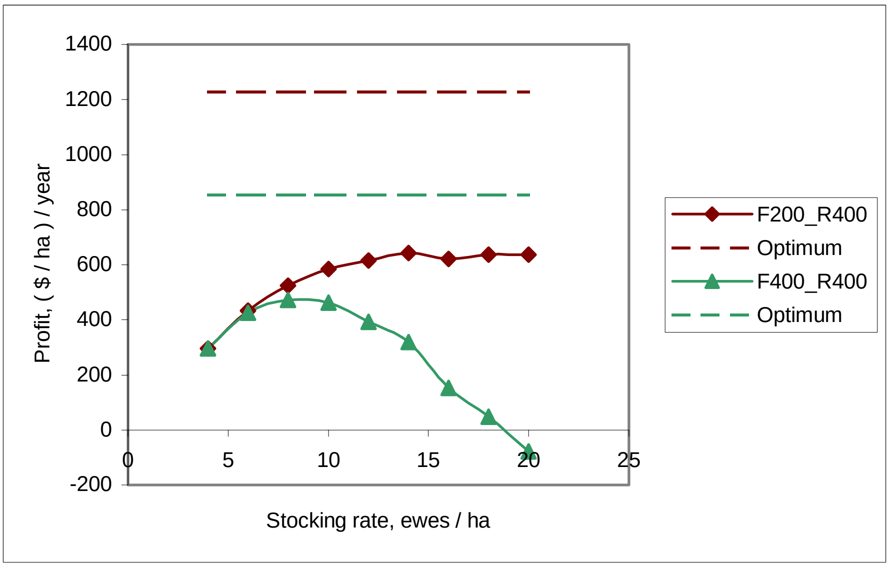


Figure 11: Comparison between variable optimum and mean of optimum stocking rate for the F200_R400 treatment.

It is clear from this graph that the model simulations with the optimum stocking density significantly out-perform using the long-term mean stocking rate as a constant stocking rate. Another feature to note is that the fixed stocking rate graph with low feed cost (F200_R400) seems to approach an asymptote. Our interpretation of this is that eventually animal intake is predominantly as supplementary feed and so there is a relatively uniform return on supplementary feed at this low cost. Clearly other factors will come into play as the stocking rates increase, such as infrastructure costs for dealing with large numbers of animals. However, given the dramatic decline in profit for the F400_R400 treatment, it may be inferred that the high stocking rates when feed costs are low present a risk if there is a likelihood of supplementary feed costs increasing.

Milestone 6: General assessment of the techniques

In this project we have incorporated DE techniques into the SGS Pasture Model to look at four key areas:

- model parameter estimation;
- system optimisation;
- constrained optimisation;
- and risk analysis.

These are considered in turn.

Parameter estimation

The particular problem that was addressed was to estimate soil physical characteristics by using direct measurements of soil water content through the soil profile and through time and then fitting the predicted and measured values for soil water content. The method seemed to work well although we did recognise the possibility of errors in other components of the model influencing the results. In addition, it is important that the range of water contents should cover the range of influence of the parameter values.

Our conclusion is that there is considerable potential for the approach but that it may be more effective to be applied under short-term wetting and drying experiments. This will reduce the influence of aspects such as estimates of evapotranspiration and will also allow control over the range of water contents being analysed. A further advantage will be that once these parameters have been derived and used in the full simulation model, when discrepancies between predicted and measured soil water content are observed it may be possible to identify other components of the model, or observational data, that can be improved.

We were also aware of the importance of accurate measurements of soil water content. This is almost universally measured by indirect methods (rather than actually drying the soil directly), as this is the only way to get long-term sequential values. However, indirect measurements do require accurate calibration and this can be challenging, as discussed by Johnson *et al,* (2003). Even rainfall can be difficult to measure and is subject to considerable spatial heterogeneity.

The model provides a powerful approach to work closely with observational data both to estimate underlying parameters and also to assess the accuracy of model assumptions and experimental data.

System optimisation

The climate in parts of Australia is highly variable so that pasture production is also variable. Drought is a part of life. This means that there are times where pasture growth is substantial while it may be negligible for extended periods. Stock, of course, require a regular source of quality food and so the supply of supplementary feed is an important management option.

On-farm quality fodder can be grown for around $100 to $200 per tonne. However, few graziers have such feed available in times of drought. As a result, good feed costs at present around $800 per tonne, if it can be obtained at all. There is a paradox faced by graziers: in good seasons do they focus entirely on producing livestock and making money, or do they plan for the inevitable drought?

The present analysis has shown that varying stocking rate in response to climate has clear economic advantages over attempting to maintain a constant stocking rate. While this is not particularly surprising, the extent to which it affected the results was quite dramatic: the variable stocking rate gave around double the ‘profit’ to that with fixed stocking rate. Note that in the analysis, the profit is calculated solely in terms of cash balance for buying and selling stock once per year and the cost of supplementary feed which is taken as constant throughout the simulation. Nevertheless, the results do suggest that this is an area that could benefit from further analysis.

In our analysis, we had the luxury of knowing future climatic patterns, which is clearly not realistic. However, by analysing the past we have the opportunity to explore trends and patterns and so assess the viability of a range of strategies that can be applied in the future.

Constrained optimisation

While system optimisation is an important objective, care must be taken to ensure that the strategies so derived do no have a detrimental environmental effect. The particular interest here has been land degradation that can occur from over-grazing. While pasture persistence is not incorporated in the Model we have been able to explore the impact of imposing the constraint of minimum ground cover on the simulations. This generally will require that supplementary feed be applied at a time when there is still sufficient pasture available for the animals to graze.

Our results showed that if supplementary feed is relatively inexpensive then there is little to be lost by maintaining good ground cover. Even when the cost of feed rises, the penalty is relatively small. If we were to incorporate the costs associated with pasture degradation, such as pasture re-establishment, it is quite likely that maintaining good ground cover presents no financial penalty and may actually be more financially viable.

Variable stocking rate management strategies do require the ability to buy and sell stock as desired, and this is not always the case. However, as mentioned above, if we are confident that the Model and DE can find optimum strategies under these simplifying assumptions, this gives us confidence that the approach can be used to analyse the system under more realistic conditions.

Risk analysis

Risk analysis is the natural extension of system optimisation. Once we know the optimum management strategy (subject to various conditions and constraints), we can then analyse the risk of more general approaches. In the exploratory analysis presented here, we compared long-term set stocking with the variable stocking approach. It was clear that the set-stocked approach can result in considerable risk when substantial levels of supplementary feed are required. While this only confirms what is well known, the fact that the DE analysis gives consistent and realistic outcomes gives us confidence that management strategies can be analysed for long-term risk using the model.

Concluding remarks

This has been a challenging, exciting and rewarding project. The linking of DE techniques with the Model has worked well for a range of applications and, as a *proof of concept* project we are confident that there is excellent potential for further development.

One of the limitations we have faced is the computational time required for the optimisation. The Model is broad in its scope, covering the pasture, water, nutrient and animal components of the system. It does run quite fast, taking around 1 second per year on a 1.2 GHz machine, but this does mean that optimisations can take around an hour or so. There is potential to speed the program in a number of ways. All processes are calculated with a daily time-step and this could be relaxed in some cases. For example, animal metabolism could use a weekly time-step although intake could be calculated daily. This could also be applied to the nutrient dynamics, particularly organic matter turnover. Apart from these possibilities, it is perhaps timely to give the Model a thorough overhaul which will inevitably improve its efficiency. This, combined with a more recent processor should allow about a 10 fold increase in simulation speed which would be substantial.

The analysis has only considered a single paddock, whereas there are clear indications of the benefit of rotational grazing. We have the potential to extend the Model to be applied to multiple paddocks and to incorporate flexible rotational grazing management strategies. For example, if there is an on-farm approach to producing feed for drought (eg hay and silage), it may be possible to restrict any pasture degradation to a small area of the farm while still being able to feed the stock. Given the inevitability of drought for many Australian graziers, the methods developed here have the potential to explore long-term strategies for dealing with drought.

In summary, we feel that the project has clearly demonstrated the viability of this type of analysis. To our knowledge, this is the first time that a biophysical model of this nature has been combined with optimisation techniques to explore a range of problems. We have found the collaboration very stimulating and hope to be able to continue to develop this type of work further to the benefit of the Australian meat and livestock industry.

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