Sustainability, externalities and economics: the case of temperate perennial grazing systems in NSW

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Abstract: The replacement of perennial grass species by undesirable annual grass weeds not only results in lower productivity but is also contributes to a range of external costs. In particular, shallow rooted annuals result in greater deep drainage and therefore a greater potential for salinity, and greater volumes of runoff of poor quality water to streams. In this paper an economic framework for examining the sustainability issues of a perennial grazing system on the NSW Central Tablelands is presented. This involves a combination of simulation and dynamic programming models, with the state of the system represented by variables for the perennial grass composition and soil fertility. The paper examines a range of management strategies that increase the perennial grass composition in terms of net income from grazing, and the impact upon the externalities.

Keywords: perennial pasture; sustainability; externalities; bioeconomic modelling; dynamic programming

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Executive Summary

There have been significant declines in the perennial grass content in native and sown pastures across temperate Australia. Not only has this reduced agricultural productivity, but has contributed to a range of external costs associated with serious degradation such as loss of soil and biodiversity, decreasing water quality, and dryland salinity caused by rising watertables. This paper presents an economic framework for examining a range of on-farm production and environmental issues in a perennial grazing system in the New South Wales temperate perennial pasture zone. This involves a combination of simulation and dynamic programming models, with the state of the system represented by variables that measure the perennial grass composition and soil fertility. The paper considers a range of management strategies that increase the perennial grass composition in terms of net income from grazing, and the impact upon externalities. The study concludes that long-term economic returns are improved by strategies that lead to an increase in perennial grass composition over time. The study also determined that environmental factors such as deep drainage, runoff and soil loss are reduced as perenniality is increased. However, the study suggests that it not appropriate to claim that the grazing systems are actually 'sustainable'. The concept of a sustainable agricultural system can only be considered at an industry or a catchment level, not at paddock or farm scale studies as reported here. Consequently, we suggest that there are positive economic and environmental effects from the adoption of grazing systems that result in greater perenniality, however we are unable to discern the overall impact upon the catchment processes from such adoption and whether agriculture is more sustainable as a result.

1. Introduction

The temperate perennial pasture zone (TPZ) in New South Wales, Australia (>600 mm annual rainfall) is a major sheep and cattle production area. This region represents about 5 million hectares, sustains 23 million sheep and 3.5 million cattle, and contributes significantly to the New South Wales economy (Vere *et al*., 2002). There are a number of serious land degradation issues now facing agricultural systems in this region, in particular the decline in the perennial grass component and a range of external costs through changed water use patterns.

Pasture degradation due to a decline in the perennial grass content may be characterised by increased variability in production over time, poorer summer forage supply, weed invasions, more rapid soil acidification and the increased development of salinity through poor management of the watertable (Kemp *et al*., 2000). Vere (1998) found that there has been a decline in production from improved pastures in the TPZ. This was largely attributable to the decline in perennial grass and legume content due to invasion by annual grass weeds.

Soil related problems pose a significant sustainability challenge for the temperate perennial grazing industries with significant impacts already evident. For example, earlier studies found that soil acidity was limiting crop and pasture production on an area exceeding 7 million hectares (Helyar *et al*., 1990). The TPZ is also a major source of watertable accessions within the Murray-Darling Basin, the largest and most developed river system in Australia and accounting for 13% of the continent. Tree clearing to develop native and sown pastures for livestock grazing is suspected of increasing the threat of salinisation lower in the catchment through contributions to rising ground water levels (Gates and Williams, 1988).

The replacement of shallow rooted annual species with perennials can substantially reduce soil acidification and water losses from deep drainage in pasture systems (Ridley *et al*., 2001; Ward *et al*., 2001). Pasture systems with a high proportion of perennial species have also been demonstrated to provide significantly higher financial returns (Dowling *et al*., 2001; Dowling and Jones, 2002). Consequently, developing and maintaining a strong perennial grass component in pastures is a key objective to achieving a sustainable grazing system.

There are a number of management options that can be adopted by landholders to achieve this objective. These include reducing stocking rates of sheep and cattle so that grazing pressure on desirable perennial grass species is minimised, tactical rests to rehabilitate the perennial component, resowing of the pasture with perennial species when the composition gets to a low level, and herbicides to control undesirable weed species such as annual grasses (eg. *Vulpia* spp., *Bromus* spp.) and broadleaf weeds (eg. *Echium* spp.). Also, soil fertility levels can be manipulated through the application of phosphorus and nitrogen fertilisers, as well as lime, so as to manipulate the competitive relationships between the desirable and undesirable species. Finally, at a catchment level a policy of withdrawing parts of the landscape from agriculture and revegetation with trees for a better watertable balance may be considered.

Michalk *et al*. (2003) presented the results of a multi-disciplinary research program conducted in central New South Wales over the period 1997-2001. The aim of this research was to develop more profitable and sustainable management systems for perennial grass based pastures by imposing tactical management strategies. The treatments were based upon the application of phosphorus fertiliser and strategic grazing rests where paddocks were destocked over summer.

The concept of strategic grazing rests for improving the composition of perennial grasses in a pasture system was developed from a number of earlier studies (Dowling *et al*., 1993; Dowling *et al*., 1996; Kemp *et al*., 1996). In a broader context, modifying botanical composition by imposing management changes such as fertiliser inputs or by varying grazing strategies (stocking rate, various forms of rotational grazing) has been known for some time in European agriculture (Jones, 1933; Voisin, 1960). Implementation of this approach in temperate Australia has been delayed largely because good husbandry was not required when desired botanical composition could be reimposed by simply replanting the pasture. A decline in the cost-effectiveness of replanting over the last 20 years (Vere *et al*., 1997), and the increasing need to retain perenniality in pastures (Ridley *et al*., 1997) based on either exotic or native grass species has forced a reassessment in the way we manage pastures, and the need to regard pastures as a long-term investment.

More recent studies have confirmed the utility of grazing rests as a means of varying pasture composition, and increasing and maintaining long-term perenniality (Graham *et al*., 2000; Virgona *et al*., 2000; Michalk *et al*., 2003), though universality of response by species and season would appear to be dependent on local conditions (Kemp *et al*., 2000). The response by perennial grasses is closely associated with the timing of the grazing rest in relation to reproductive activity of the target species, and is enhanced by longer rests and more favourable conditions at the time of the grazing rest (Virgona and Bowcher, 2000).

The objective of this paper is to present an economic framework suitable for evaluating the economic benefits of technologies that increase perenniality and to examine the sustainability issues associated with grazing systems in the TPZ. A number of policy options for achieving increased perenniality are considered. These are a polluter-pays and beneficiary-pays approaches, and direct regulation.

A case study approach is used to determine the economic benefits and sustainability impacts of fertiliser and grazing management tactics in the TPZ. The case study region is the Central Tablelands of New South Wales, Australia. This region was selected because of the availability of suitable soil data and long-term daily weather data as well as the results from a number of locally based experimental studies.

2. Methods

2.1 Defining sustainability

There are many definitions of sustainability or sustainable economic development. Also, the term sustainability has a wide range of interpretations with Graham-Tomasi (1991) pointing out ‘just about everyone is on the sustainability bandwagon, and sustainability has come to mean all things to all the riders on this bandwagon’.

The most widely used definition of sustainable development is that put forward by the World Commission on Environment and Development, which is ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (WCED, 1987, pp. 43). Many more definitions exist, with Pezzey (1992) listing 27 definitions of sustainable development. From an Australian perspective the National Strategy for Ecologically Sustainable Development defines ecologically sustainable development as ‘using, conserving and enhancing the community’s resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased’ (Commonwealth of Australia, 1992, pp. 6).

There are two potential versions of sustainability; strong sustainability and weak sustainability (Turner *et al*., 1994, pp. 55; Stoneham *et al*., 2003). The main difference between these two versions is the ability to make trade-offs between the various forms of capital (natural, human and social). In the case of strong sustainability the stocks of natural capital must not be depreciated over time, i.e. the same stock of resources available to current generations will be available to future generations. The concept of weak sustainability allows for substitution between the different forms of capital stock, thereby allowing an overall economic system to be sustainable by trading-in some forms of capital for others.

Central to the issue of sustainability is the question of the rights of future generations. The strong sustainability condition requires that the same physical stock of resources be available to future generations, which may not only be impractical but economically may not be in the current or future generations best interests. According to Solow (1986) “The current generation does not especially owe its successors a share in this or that resource. If it owes anything, it owes generalised productive capacity or, even more generally, access to certain standards of living or level of consumption (p 142)”. Mullen and Bathgate (2002) provide a comprehensive review of the arguments regarding the rights of future generations to access of natural resources, along with a review of the issue of resource scarcity.

Pannell and Schilizzi (1999) in referring to the multitude of definitions in the literature conclude that sustainability is not a useful criterion in itself for planning or decision making. However, the term sustainability is useful as an emblem for other criteria that capture the relevant issues pertaining to resource and environmental management.

Rather than be overly concerned with exact definitions of sustainability or sustainable development, a better approach may be to accept the goal of sustainability in a general sense to be an improvement in the productive performance of a system without depleting the natural resource base upon which future performance depends (Pearce and Turner, 1990, pp. 24). This is consistent with the views of Graham-Tomasi (1991) and Pannell and Schilizzi

(1999) that sustainability should be viewed as a goal rather than as a set of actions or technologies. Sustainability generally involves several separate issues such as protection of ecological systems, inter-generational equity and efficiency of resource use (Pannell and Schilizzi 1999), valuation of environmental assets and recognition of constraints implied by the dynamics of environmental systems (Heal 1998, p48). Given the diversity of issues, sustainability is difficult to measure and it is not possible to identify a few key variables at the farm level which adequately gauge sustainability (Graham-Tomasi 1991).

Heal (1998, pp. 48) suggests that the essence of sustainability is defined by the following three axioms.
(i) A treatment of the present and the future that places a positive value on the very long run.
(ii) Recognition of all the ways in which environmental assets contribute to economic well-being.
(iii) Recognition of the constraints implied by the dynamics of environmental assets.

These points have significant implications for the frameworks that are suitable for assessing the sustainability problem. Consequently, dynamic models that consider a reasonable period of time (eg. 20 to 30 years) would appear more appropriate than single period simulation or optimisation models. The choice of components within the objective function also needs to be carefully considered. Incorporating preservation values or external costs associated with resource management are important in determining optimal policies or decisions from a sustainability viewpoint.

2.2 A bioeconomic model of sustainable grazing

Understanding the long-term implications of managing a resource or environmental asset is one of the key components of the sustainability problem. Pandey and Hardaker (1995) present a framework that incorporates the inter-temporal tradeoffs for evaluating the sustainability problem into a bioeconomic model.

$$\max \quad J = \sum_{t=0}^{T} \pi(x_t, u_t)\delta^t \qquad (1)$$

subject to

$$x_{t+1} - x_t = g(x_t, u_t) \qquad (2)$$

$$x_0 = x(0) \qquad (3)$$

$$x_t \geq X_T \qquad (4)$$

Where J is the discounted sum of the performance measure over the planning horizon T, t is an index for year, π is a measure of farm performance, x is the stock of natural resources (state variables), u is the set of management decisions (control variables), δ is the discount factor ($\delta = 1/(1+r)$, r is the discount rate), and g is the measure of the change in the stock of the natural resources over time, which depends on the stock size and the management decisions. The final constraint (equation 4) reflects the requirement of a strong sustainability definition, where the stock of the resource is no less than some specified stock of the resource (X_T). In the case of a weak sustainability system the value of X_T in equation 4 is set to zero, with emphasis being on valuing the trade-offs between the sets of resource capital.

Heal (1998, p36) argues that society may experience economic value from the existence of a resource or environmental good in addition to the benefits derived from consumption of the stock of the resource over time. An example is a forest which is conventionally valued as the flow of wood for consumption. However, the forest can also be valuable as a source of biodiversity, carbon sequestration services, and as a recreational facility. Consequently, it may be important to include the preservation benefits of a resource along with any consumption benefits. In the case of a perennial grass based grazing system, environmental benefits associated with the stock of a perennial grass resource can be partly attributable to a reduction in externalities such as reduced deep drainage to the watertable (and thereby less catchment salinity), improved quality of streamflow runoff, and greater biodiversity.

A dynamic programming model was developed for the sustainable grazing management problem and is outlined as follows.

$$\max \quad J = \sum_{t=0}^{T} \pi\left(PG_t, P_t, SR_t, F_t\right)\delta^t \tag{5}$$

subject to

$$PG_{t+1} - PG_t = f_1(PG_t, P_t, SR_t) \tag{6}$$

$$P_{t+1} - P_t = f_2(P_t, F_t) \tag{7}$$

$$PG_0 = PG(0) \tag{8}$$

$$P_0 = P(0) \tag{9}$$

Where *PG* is the proportional composition of perennial grasses in the pasture, *P* is the level of soil phosphorus, *SR* is the livestock stocking rate (head/ha), and *F* is the amount of phosphorus fertiliser applied (kg/ha).

Three policy approaches are used to investigate the sustainability problem in perennial grazing systems.

(i) The outputs of deep drainage, runoff and soil loss are considered as external costs in the objective function. This treats the issue as a polluter-pays approach to the problem. Although deep drainage and poor quality runoff are both diffuse forms of pollution and in practice it would be difficult to identify and impose pollution taxes, this analysis is useful in terms of determining the potential change in farmer behaviour from such a policy action.

(ii) Following the approach of Heal (1998) a preservation benefit associated with the variable *PG* is included in the objective function. This represents a beneficiary-pays approach to the problem if compensation or direct subsidies were used as the preservation benefit payment.

(iii) A strong sustainability constraint (equation 4) is imposed, which restricts *PG* to be greater than some specified value. Direct regulation in environmental issues is often of this type where limits or targets on resource use are imposed by government.

The interactions between the species composition and soil fertility models, which are represented by the differential equations for the state variables, with the water balance, grazing systems and dynamic programming models are illustrated in Figure 1. The water balance and grazing systems models are calculated on a daily time step whereas the species composition and soil fertility models are calculated annually. All these biological models combine to provide the necessary data for the state transitions and objective function (π) of the dynamic programming model.

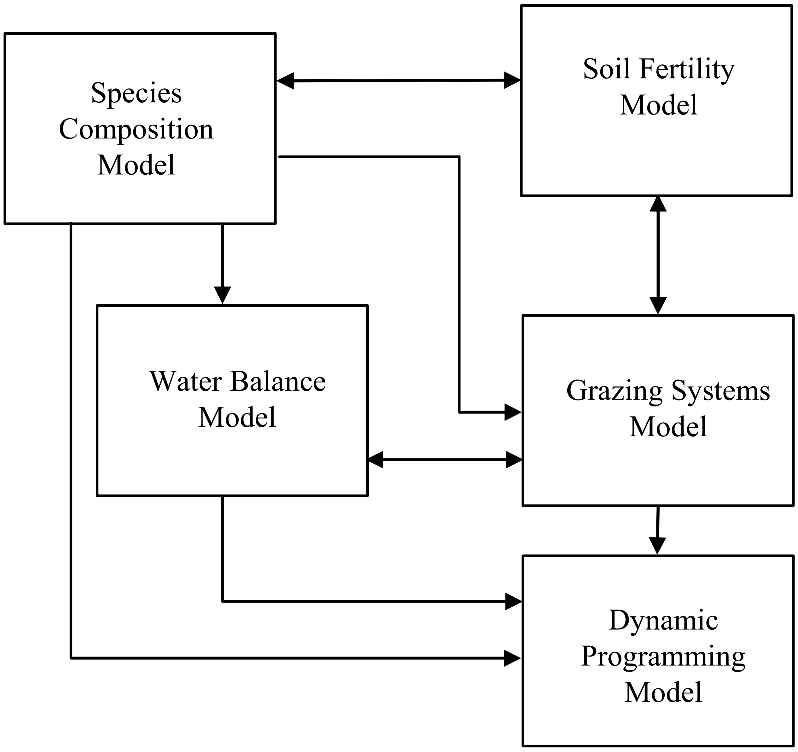

Figure 1. The sustainable grazing modelling system

The objective function of the dynamic programming model included both private and public benefit components. The model results in a socially optimal solution of resource use when the environmental costs resulting from grazing management are included.

$$\begin{aligned}\pi = &\left(LR - LC - SFC - PVC - FC\right) - \left(P_{RO}RO + P_{DD}DD + P_{SL}SL\right) \\ &+ B_P PG\end{aligned} \tag{10}$$

Where *LR* is livestock revenue, *LC* is livestock production costs, *SFC* are supplementary feed costs, *PVC* are pasture variable costs, and *FC* are fertiliser application costs. The external impacts upon the environment are captured through the variables on the right hand side of equation 10. P_{RO} are unit costs associated with runoff ($/mm), *RO* is runoff amount (mm/ha), P_{DD} are unit costs associated with deep drainage to the watertable ($/mm), *DD* is the amount of deep drainage or water lost to the watertable (mm/ha), P_{SL} are unit costs associated with soil loss ($/t), SL is the amount of soil loss (t/ha), and B_P is the preservation benefit associated with PG ($/ha). A privately optimal objective function results from setting the values of P_{RO}, P_{DD}, P_{SL} and B_P to zero. The polluter-pays approach to the sustainability problem involves setting non-zero values for P_{RO}, P_{DD} and P_{SL}. For the beneficiary-pays approach these values are maintained at zero and a positive value for B_P is included.

The use of an external cost approach to the sustainability question is appropriate in this study for a number of reasons. Given the small scale of the analysis (i.e. hectare, paddock, farm), the environmental effects of management are mostly off-site and cannot be represented adequately through a state variable in the dynamic programming model. This problem could be resolved by setting the decision problem to be at a regional or catchment scale and including a state variable for the watertable or area/proportion of the catchment that is salinised (Greiner 1997). However, the processes linking on-farm water management and regional watertables in the study region are poorly understood so there is little to be gained from increasing the level of complexity in this manner at this time.

The management decisions included in the model involve a range of variables that influence both species composition and economic returns. These are: livestock stocking rates, pasture establishment costs, tactical grazing rests and fertiliser options. A description of the decisions is given in Table 1. In this study the livestock system is represented by a merino wether (i.e. sheep) enterprise.

Table 1. Description of grazing management decisions

Index	Decision	Description
1	EST	Establish pasture, fertiliser (250 kg/ha), no livestock
2	SR5	Continuous stocking rate at 5.0 LU/ha
3	SR7.5	Continuous stocking rate at 7.5 LU/ha
4	SR10	Continuous stocking rate at 10.0 LU/ha
5	SR12.5	Continuous stocking rate at 12.5 LU/ha
6	SR15	Continuous stocking rate at 15.0 LU/ha
7	GR0	Grazing rest – all year
8	GR5	Summer grazing rest, stocking rate at 5.0 LU/ha remainder
9	GR7.5	Summer grazing rest, stocking rate at 7.5 LU/ha remainder
10	GR10	Summer grazing rest, stocking rate at 10.0 LU/ha remainder
11	GR12.5	Summer grazing rest, stocking rate at 12.5 LU/ha remainder
12	GR15	Summer grazing rest, stocking rate at 15.0 LU/ha remainder
13	FSR5	Fertiliser (125 kg/ha) + SR5
14	FSR7.5	Fertiliser (125 kg/ha) + SR7.5
15	FSR10	Fertiliser (125 kg/ha) + SR10
16	FSR12.5	Fertiliser (125 kg/ha) + SR12.5
17	FSR15	Fertiliser (125 kg/ha) + SR15
18	FGR0	Fertiliser (125 kg/ha) + GR0
19	FGR5	Fertiliser (125 kg/ha) + GR5
20	FGR7.5	Fertiliser (125 kg/ha) + GR7.5
21	FGR10	Fertiliser (125 kg/ha) + GR10
22	FGR12.5	Fertiliser (125 kg/ha) + GR12.5
23	FGR15	Fertiliser (125 kg/ha) + GR15

LU = livestock unit; Fertiliser = single superphosphate (9.1% P)

2.3 The species composition model

The state of the pasture system is defined by three species functional groups; perennial grasses (*PG*), legumes (*LG*) and annual weeds (*AW*). The *PG* and *LG* comprise the set of desirable species in the grazing system, while *AW* represents the set of undesirable species. The *PG* functional group includes all C3 and C4 (native and introduced) perennial grass species, while *AW* represents annual grasses (eg. *Vulpia* spp., *Bromus* spp.) and broadleaf weeds (eg. *Echium*). Combining the annual grasses and broadleaf weeds simplifies the modelling process and is biologically justifiable given the similar responses by both annual grasses and broadleaf weeds to the management options evaluated (eg. Dear *et al.*, 1998). A pasture state variable is defined to represent the composition of the desirable perennial grass species. This variable takes values between zero and one, and represents the proportional composition of the pasture biomass as at 1 September for each year. Given that all species are at a similar stage of growth on this date this approach is considered to give the best representation of the space, or ecological field, occupied by the PG functional group. The remaining space is assumed to be occupied by legumes and annual grass and broadleaf weeds.

A growth equation approach (Fitzpatrick and Nix, 1970) was adopted to measure the annual rate of change in *PG* (Δ*PG*). Two logistic equations were used to calculate Δ*PG*, depending on whether the value of *PG* is above or below a pre-specified asymptote. If composition is below the asymptote a growth equation is used, whereas if composition is above the asymptote a decay function is adopted.

$$\Delta PG = \begin{cases} b_1 \times PG_t\left(aFI - PG_t\right) & \text{for } PG_t \le a \\ -\left[b_2\left\{b_3 - \left(PG_t - a\right)\right\}\left(\left\{PG_t - aFI\right)\right] & \text{for } PG_t > a \end{cases} \qquad (11)$$

Where *FI* is a fertility index, *a* is an asymptote while b_1, b_2 and b_3 are shape parameters for the logistic equations. The annual change in the value of the species state variable is derived from the following differential equation.

$$PG_{t+1} = PG_t + \Delta PG \qquad (12)$$

Table 2. Logistic equation parameters for grazing decisions

Decision	a	b_1	b_2	b_3
EST	0.00	0.00	0.00	0.00
SR5	0.55	1.00	0.50	0.50
SR7.5	0.45	1.00	0.50	0.50
SR10	0.30	1.00	0.50	0.70
SR12.5	0.25	1.00	0.50	0.70
SR15	0.20	1.00	0.65	0.80
GR0	0.80	1.00	0.50	0.50
GR5	0.80	0.70	0.50	0.50
GR7.5	0.70	0.70	0.50	0.50
GR10	0.65	0.70	0.50	0.50
GR12.5	0.60	0.70	0.50	0.50
GR15	0.50	0.70	0.50	0.70

The values for the logistic equation parameters are given in Table 2. These values were obtained from a combination of estimating parameters from experimental data for selected decisions, and by extrapolation for the remaining decisions based upon expert opinion.

2.4 The soil fertility model

The fertility index was based upon the approach of Holford (1980) for estimating relative yield as a function of soil (Bray1) phosphorus. Holford defined relative yield as the proportion of maximum (unconstrained by phosphorus) yield.

$$FI = \frac{a_1 a_2 P}{1 + a_1 P} \tag{13}$$

Where a_1 is a slope coefficient, a_2 is the asymptote (Table 3) and P is the level of soil phosphorus measured in mg/kg, or parts per million (ppm). The FI variable is used in the calculations of the daily growth of specific pasture species and the calculation of the rate of change in the composition of perennial species. Following the findings of Holford and Crocker (1988) separate FI were calculated for ΔPG as well as for the pasture growth rate equations for perennial species, legumes and annual weeds.

Table 3. Fertility index parameters

	a_1	a_2
PG	0.25	1.10
LG	0.15	1.15
AW	0.75	1.02
ΔPG	0.30	1.15

The effect of applied fertiliser is to raise the amount of phosphorus in the soil, while there is an ongoing annual loss in phosphorus due to grazing. The calculation of the annual transition in soil P follows that of Kriticos (unpublished), which is partly based upon the findings of McCaskill and Cayley (2000). The amount of phosphorus at the start of a year (P_t) is a function of phosphorus in the previous year ($P_{t\text{-}1}$), the annual loss in phosphorus (P_{loss}) and fertiliser applied (P_{fert}).

$$P_t = P_{t-1} + \left(P_{fert} P_c\right) - P_{loss} \tag{14}$$

Where P_c is the proportion of P available in phosphorus fertiliser ($P_c = 0.091$), P_{fert} is measured in terms of kg/ha and the remaining variables in ppm. The variable P_{loss} is represented by the following decay function.

$$P_{loss} = a_3\left(P_t - P_{\min}\right) \tag{15}$$

Where a_3 is a decay coefficient ($a_3 = 0.1852$) and $P_{\min}$ is a minimum amount of phosphorus fertiliser available from non-expendable pools of phosphorus ($P_{\min} = 3$).

2.5 The water balance model

The environmental parameters used in growth index (*GI*) calculations and the environmental effects from grazing management systems were derived from the PERFECT model (Littleboy *et al*., 1999). PERFECT (Productivity, Erosion and Runoff Functions to Evaluate Conservation Techniques) is a biophysical model that simulates the plant-soil-water-management dynamics in an agricultural system. In addition to calculating daily soil moisture the model was used to determine runoff, soil loss and deep drainage to the watertable for a range of perennial and annual vegetation systems.

PERFECT uses daily weather inputs for precipitation, maximum temperature, minimum temperature, pan evaporation and solar radiation. Weather data were obtained for the period 1930 to 2002 for Orange, Central Tablelands, (Lat -33.28, Long 149.10 decimal degrees) from the Silo dataset (http://silo) for use in the model.

Given the diversity of soil types within the study region, the PERFECT model was solved for two distinct soil types; ferrosol and kurosol. Ferrosol soil types are derived from basalt, are highly fertile and have high water holding capacity. Kurosol soil types are granite based and have greater drainage potential than ferrosols. Both soil types are widespread within the TPZ.

2.6 The grazing systems model

The interaction between the growth of individual pasture species and livestock feed requirements was determined using a daily time step grazing systems simulation model. This model system also determined the financial returns from the livestock enterprise, including the cost of supplementary feeding when pasture feed supply was less than livestock daily demand.

A pasture is usually a mixture of species in the field as it is rare in grazing systems that a particular species will occur as a monoculture. Consequently, the challenge is to progress from biomass accumulation from a single-species growth rate equation, to biomass accumulation for a pasture system with a number of distinct species components. The approach taken in this study is now described. The indexes used in the equations are defined as:

τ = time index (daily)
k = species index (1 … 6)
i = growth stage index (1 ... 5)
z = season index (1 … 4)

The grazing systems model is calibrated to produce predictions of actual dry matter production using a growth index as a constant in the following logistic growth rate equation.

$$\frac{dW}{d\tau} = S \times GI_{\tau} \times W_{\tau}\left(W_{\max} - W_{\tau}\right) \qquad (16)$$

Where S is a species dependent constant, GI is a species specific daily growth indexes derived from the water balance model, W is the weight of dry matter, and $W_{\max}$ is the limiting biomass. The values for S, $W_{\max}$ and W_0 (the initial dry matter) for each species are presented in Table 4.

Table 4. Logistic growth equation parameter values

	$W_{\max}$	W_0	S
Introduced perennial grass (C3 mesotherm)	15,000	2,500	0.0000055
Native C3 perennial grass (C3 mesotherm)	14,000	2,500	0.0000045
Native C4 perennial grass (C4 megatherm)	12,500	2,000	0.0000075
Sub-clover (C3 mesotherm)	11,000	300	0.0000045
Vulpia (C3 mesotherm)	15,000	100	0.0000040
Echium (C3 mesotherm)	15,000	100	0.0000040

A number of plant growth stages were specified to represent the fact that digestibility and metabolisable energy differ for various stages of the plant life-cycle. The stages used in the study are a simplification of the seven stages of growth defined by Prograze (1995) and are; 1 – active green growth, 2 – late vegetative, 3 – early flowering, 4 – late flowering (in head), and 5 – dry stalks. This approach is similar to that used in the GrassGro modelling system (Moore *et al*., 1997), which classifies shoot material into five digestibility classes.

Rather than track the complexity of the transfers of biomass from one digestibility pool to the next, and between plant tissue states, the total biomass was apportioned into the various growth stages on the basis of season. For instance, during the autumn months it is expected that a large proportion of perennial C3 plant biomass is in a green vegetative stage, whereas in summer, biomass is largely either in the flowering or dry stalks stage. The proportional breakdown of total biomass into the individual growth stages for C3 perennial grass, C3 annual species and C4 perennial grass is given in Table 5.

Table 5. Proportion of biomass at each stage and season

Growth stage	Autumn	Winter	Spring	Summer
C3 perennial grass				
1	0.3	0.4	0.1	0.0
2	0.5	0.6	0.3	0.2
3	0.0	0.0	0.5	0.0
4	0.0	0.0	0.1	0.4
5	0.2	0.0	0.0	0.4
C3 annual species				
1	0.3	0.4	0.1	0.0
2	0.5	0.6	0.2	0.1
3	0.0	0.0	0.6	0.0
4	0.0	0.0	0.0	0.4
5	0.2	0.0	0.1	0.5
C4 perennial grass				
1	0.2	0.4	0.0	0.0
2	0.5	0.6	0.3	0.1
3	0.1	0.0	0.5	0.2
4	0.0	0.0	0.2	0.3
5	0.2	0.0	0.0	0.4

The daily proportion of biomass for each growth stage is calculated using linear interpolation as follows.

$$C_{ik\tau} = C_{ik\tau-1}\left(\frac{C_{z+1} - C_z}{NDAYS_z}\right) \tag{17}$$

Where C is the percentage composition of biomass for species k into growth stage i, $NDAYS$ is the number of days in the zth season ($NDAYS = \{90,91,92,92\}$), and C_{ik} is the biomass compositions of species k for each season.

The concept of digestibility is often used to represent pasture quality. Digestibility, expressed as a percentage, provides a prediction of the pasture consumed that actually might be used by the animal. Digestibility differs between pasture species and varieties, parts of a plant and by the stage of growth. Legumes generally have higher digestibility than grasses and introduced C3 grasses have higher digestibility than C4 grasses. The stage of growth of pasture plants has a major influence on digestibility with the highest digestibility associated with young actively growing plants in the vegetative stage. Digestibility declines as plants mature, particularly as they enter their reproductive phase and prepare to flower. Following flowering, the plant commences senescence and digestibility declines more rapidly. For each growth stage there is a specific value of digestibility associated with each species.

Digestibility is directly and positively related to the energy content of a pasture, assessed as megajoules of metabolisable energy per kilogram of dry matter (MJ ME/kg DM). The digestibility values are converted to metabolisable energy using the following equation.

$$MEV = 0.0854D + 0.0008D^2 \tag{18}$$

Where MEV is metabolisable energy (MJ ME/kg) and D is the digestibility value of plant dry matter. The polynomial equation (18) was estimated from digestibility and metabolisable energy data showing equivalence in energy values (Prograze, 1995). The values for digestibility and metabolisable energy used in the study for each species and growth stage are given in Table 6.

Table 6. Digestibility (D_{ik})and metabolisable energy (MEV_{ik}) (MJ ME/kg DM) of species by stage of growth

	Species (*k*)					
Growth stage (*i*)	Introduced C3 perennial	Native C3 perennial	Sub-clover	Vulpia	Echium	Native C4 perennial
D						
1	80	80	85	75	75	75
2	73	73	78	65	65	68
3	68	68	73	45	45	60
4	60	60	65	40	40	45
5	55	55	60	0	0	25
MEV						
1	11.95	11.95	13.04	10.91	10.91	10.91
2	10.50	10.50	11.53	8.93	8.93	9.51
3	9.51	9.51	10.50	5.46	5.46	8.00
4	8.00	8.00	8.93	4.70	4.70	5.46
5	7.12	7.12	8.00	0.00	0.00	2.64

There are a number of complex interactions between plant growth, plant biomass and livestock pasture consumption that need to be adequately accounted for in determining the performance of the grazing system. These relationships are outlined as follows.

Pasture biomass:

$$W_\tau = \sum_{k=1}^{6} SW_{k\tau} + \Delta G_{k\tau-1} \tag{19}$$

$$SW_{k\tau} = \sum_{i=1}^{5} B_{ki\tau} \tag{20}$$

Where *W* is the total biomass of the pasture sward (kg/ha), *SW* is the biomass of species *k* (kg/ha), ΔG is the growth as calculated by the growth rate equation (kg/ha/day), and *B* is the biomass of the *i*th growth stage of the *k*th species (kg/ha). The biomass calculated for each growth stage is a function of the total species biomass (*SW*), the percentage of biomass that corresponds to that growth stage (*C*), and consumption of biomass by livestock. The specific equations used for the growth stage biomass calculations follow.

Stages 1-4:

$$B_{ik\tau} = \left(SW_{k\tau}C_{ik\tau}\right) - \left(PC_{k\tau-1} \times \frac{B_{ik\tau-1}}{SW_{k\tau-1}}\right) \tag{21}$$

Stage 5:

$$B_{ik\tau} = \left(SW_{k\tau}C_{ik\tau} - B_{ik\tau-1}SN_k\right) - \left(PC_{k\tau-1} \times \frac{B_{ik\tau-1}}{SW_{k\tau-1}}\right) \tag{22}$$

Where *PC* is the total amount of species *k* consumed by livestock (kg/ha), and *SN* is the senescence factor for species *k*.

Growth rate:

$$\Delta G_{k\tau} = \begin{cases} 0 & \text{if } SW_{k\tau} = 0 \\ \left[S_k \times GI_\tau \times W_\tau\left(WMAX_k - W_\tau\right)\right] \times COMP_k \end{cases} \tag{23}$$

Where *GI* is the growth index, *WMAX* is the upper limit on plant biomass for species *k*, and $COMP_k$ is the percentage composition of species *k*. This growth equation differs to the standard growth equation (16) in two aspects. First, growth is determined by the biomass of the entire sward (*W*) and not just by the individual species within that sward (SW_k). This is to reflect the fact that in a pasture made up of a number of species, growth of any single species will be influenced by competition from the other species and thus total sward biomass is a better basis for measurement of a species growth rate. Second, the amount of new growth is influenced by the species composition within the sward. The total amount of new growth is simply the sum of the new growth for each species.

$$\frac{dW}{d\tau} = \sum_{k=1}^{6} \Delta G_{k\tau} \tag{24}$$

Metabolisable energy of pasture:

$$TME_{\tau} = \sum_{k=1}^{6} ME_{k\tau} \tag{25}$$

Where *TME* is the total metabolisable energy of the pasture (MJ ME/ha), and ME_k is the metabolisable energy of the *k*th species (MJ ME/ha). This equation illustrates that the total metabolisable energy from the pasture is the sum of the energy provided by each species. The metabolisable energy of each species is found by multiplying the biomass of each growth stage by the metabolisable energy for that growth stage.

$$ME_{k\tau} = \sum_{i=1}^{5} B_{ik\tau} MEV_{ik} \tag{26}$$

Where MEV_{ik} is the metabolisable energy value for species *k* and growth stage *i*. The average metabolisable energy per kilogram of dry matter provided by the total pasture (*TMEKG*) and for each species (*MEKG*) is calculated as follows.

$$TMEKG_{\tau} = \frac{TME_{\tau}}{W_{\tau}} \tag{27}$$

$$MEKG_{k\tau} = \frac{ME_{k\tau}}{SW_{k\tau}} \tag{28}$$

Livestock graze selectively, that is they show a preference for particular plant species within a pasture and for a particular part of the plant. Consequently, livestock will not consume different species equally or in proportion to their biomass availability. The approach taken has been to assume that livestock will selectively graze primarily on the basis of the metabolisable energy of the species. Although this is a simplification of the process, as other factors such as plant height and palatability may also influence selective grazing, it is appropriate for the level of complexity accepted by this study. Consumption of the biomass of each species is weighted by the proportional contribution to total metabolisable energy of the pasture. Consequently, as a result of the selective grazing, a greater proportion of biomass of the higher feed energy species is consumed by livestock. The equations used to represent this process are as follows. The first step is to determine the contribution to the livestock energy demand by pasture and hay.

$$MES_{k\tau} = \begin{cases} 0 & \text{if } SW_{k\tau} < SW_{\lim} \\ TLME_{\tau} \times \dfrac{ME_{k\tau}}{TME_{\tau}} & \end{cases} \tag{29}$$

$$MEP_{\tau} = \sum_{k=1}^{6} MES_{k\tau} \tag{30}$$

$$MEH_{\tau} = TLME_{\tau} - MEP_{\tau} \tag{31}$$

$$HAY = \frac{MEH}{MEV_{hay}} \tag{32}$$

Where SW_{lim} is a lower limit on the biomass of any species present in the sward that is consumed by livestock, *MES* is the metabolisable energy provided by species *k* to meet livestock demand, *MEP* is the metabolisable energy provided by the total pasture, *MEH* is the metabolisable energy provided by hay, MEV_{hay} is the metabolisable energy provided per kilogram of hay dry matter, and *HAY* is the biomass of hay consumed. The lower limit on species biomass reflects the fact that at low biomass levels, livestock are unable to graze the species because it is too short. The second step is to determine the biomass consumption of each species.

$$PC_{k\tau} = \frac{ME_{k\tau}}{MEKG_{k\tau}} \tag{33}$$

$$PCON_{\tau} = \min\left[RC_{\tau} SR_{\tau}, \sum_{k=1}^{6} PC_{k\tau} \right] \tag{34}$$

Where *PCON* is the total amount of pasture consumed by livestock on day τ (kg/ha), *RC* is the rumen capacity of an individual livestock. If the total requirement of pasture dry matter by livestock exceeds a daily intake limit defined by the rumen capacity of the animals then consumption of dry matter is limited to the rumen capacity of the flock.

The feed energy demanded by livestock is calculated as follows.

$$TLME_{\tau} = SR_{\tau} \times LME_{\tau} \tag{35}$$

Where *TLME* is total livestock ME demand (MJ ME/ha), *SR* is the stocking rate (head/ha) and *LME* is the individual livestock energy demand (MJ ME/head). *LME* is derived from the generalised equations for calculating the ME requirements of livestock reported by SCA (1990). The following equation is used to calculate maintenance ME for wethers.

$$LME_{\tau} = \frac{0.26W^{0.75}e^{-0.03A}}{k_m} + 0.9MEI_{\tau} + \frac{EGRAZE_{\tau}}{k_m} + ECOLD_{\tau} \tag{36}$$

Where *W* is liveweight (kg), *A* is age in years, k_m is net efficiency of use of ME for maintenance, *MEI* is the total ME intake, *EGRAZE* is the additional energy expenditure of a grazing compared to a similar housed animal, and *ECOLD* is the additional energy expenditure in cold stress by animals in periods below lower critical temperature environments. Further details on the calculation of the parameters in equation (36) are given in SCA (1990).

Protein is important to the growth processes of meat and wool. Given that legumes are regarded as having higher protein content than perennial or annual grasses it is important to account for the greater contribution of legumes to animal growth.

The processes that govern the interaction between protein and livestock growth are complex in nature (SCA 1990; Freer *et al*., 1997). A simplified approach was used to estimate the impact of various protein contributions on wool cut per head (*WC*), whereby the relationship between wool cut per head and protein intake by livestock was derived from simulations of the GrassGro model. To simulate the influence of legume content in pasture upon wool growth a simple scalar approach was used to reflect the relationship between the legume composition in the pasture and wool cut.

$$WCUT = WBASE \times WSCALER \tag{37}$$

Where *WCUT* is the wool cut (kg/head), *WBASE* is a base value for wool cut (*WBASE* = 4) and *WSCALAR* is a scalar value calculated as follows.

$$WSCALAR = \min \begin{bmatrix} 1 + S_{\max} \\ \left(\frac{S_{\max}}{LG_{\max}} \times LG \right) + 1 \end{bmatrix} \tag{38}$$

Where $S_{\max}$ is an upper limit on the scalar value ($S_{\max}$ = 0.7), $LG_{\max}$ is the level of legume composition where the maximum wool cut (and scalar value) is expected to occur ($LG_{\max}$ = 0.5).

2.7 Model validation

It was not possible to validate the species composition model as there was only one set of data available with which to parameterise the model coefficients. Instead model verification was undertaken with groups of agronomists and pasture researchers to ensure model responses were consistent with those observed in the field. The grazing systems model was validated by comparing outputs for daily growth rates and biomass accumulation for various seasons against simulations of the GrassGro model (Moore et al. 1997) for a similar pasture system. There was reasonable consistency in pasture growth from both these models for both the average and for a series of individual years. There was not necessary to validate the PERFECT model for this study.

3. Results

3.1 Deep drainage, runoff and soil loss

The effect of the level of perennial grass composition upon deep drainage, runoff and soil loss was simulated with the PERFECT model. Two pasture scenarios were considered; (1) a pasture system that was comprised completely of perennial species, and (2) a pasture system that was comprised completely of annual species. These two scenarios represent the extremes of the composition of a pasture in the TPZ, and the actual values used in the bioeconomic model for pasture with a mixture of annuals and perennials were obtained by linearly interpolating these results.

The PERFECT model was solved for a 72-year period 1930-2002, with the summary statistics reported in Table 7. The amount of excess water (the sum of runoff and deep drainage) is largely determined by the vegetation system, being considerably less under a perennial pasture than an annual pasture. There is a soil type effect on excess water, with the ferrosol resulting in less excess water than the kurosol soil for an equivalent pasture scenario. The partitioning of the excess water is largely determined by the soil type, with a ferrosol soil having less deep drainage and more runoff than a kurosol.

Table 7. Summary statistics of PERFECT model simulations

		Percentiles		
	Mean	5th	50th	95th
Runoff (mm/ha):				
Annual pasture – ferrosol	32.0	0.0	20.5	113.6
Annual pasture – kurosol	4.6	0.0	2.1	18.8
Perennial pasture – ferrosol	25.6	0.0	14.8	97.8
Perennial pasture – kurosol	2.4	0.0	0.4	11.7
Deep drainage (mm/ha):				
Annual pasture - ferrosol	181.6	0.0	150.3	499.1
Annual pasture - kurosol	232.8	0.0	219.5	624.8
Perennial pasture - ferrosol	116.8	0.0	78.7	416.0
Perennial pasture - kurosol	168.7	0.0	135.2	533.4
Excess water (mm/ha):				
Annual pasture – ferrosol	213.6	0.0	185.1	605.6
Annual pasture – kurosol	237.3	0.3	227.5	639.1
Perennial pasture – ferrosol	142.4	0.0	92.2	491.3
Perennial pasture – kurosol	171.1	0.0	135.2	541.0
Soil loss (t/ha):				
Annual pasture - ferrosol	4.9	0.0	1.5	18.7
Annual pasture - kurosol	1.1	0.0	0.1	4.8
Perennial pasture - ferrosol	0.7	0.0	0.4	2.5
Perennial pasture - kurosol	0.1	0.0	0.0	0.4

Soil loss is heavily influenced by both the pasture and soil type. Significantly greater soil loss occurred with annual pasture, particularly on the ferrosol soil (mean 4.6 t/ha).

The 5th, 50th and 95th percentiles of the results are included in Table 7. The divergence between the 5th and 95th percentile values indicates that there is significant annual variability in the results for runoff, deep drainage and soil loss.

3.2 Private analysis of perennial grazing systems

3.2.1 Optimal decisions

The impact of ferrosol and kurosol soils was not included in the private benefit analysis as the wool production parameters driving the private objective function were not influenced by soil type. A summary of the optimal decision rules derived from the dynamic programming model for combinations of the two state variables *PG* and *P* are given in Table 8. At low *PG* levels ($PG \leq 0.10$) the optimal decision was to establish a new perennial grass pasture regardless of the prevailing level of soil *P*. Grazing rest tactics were adopted for levels of *PG* between 0.15 and 0.50, depending upon the value of *P*. At the higher levels of *P*, the grazing rest was selected at larger prevailing values of *PG*. This result indicates that there is an interaction between the levels of *PG* and *P* in determining the optimal grazing management decision.

The optimal fertiliser decision was also dependant upon the interaction of *PG* and *P*. At values of *P* between 5 and 10 mg/kg, a fertiliser application was selected for most values of *PG* considered. However, even at moderate to high *P* levels of 25 to 30 mg/kg a fertiliser application was selected for some values of *PG* ($PG = 0.20$ to 0.60).

Table 8. Optimal private decision rules for combinations of the two state variables perennial grass composition (*PG*) and soil phosphorus (*P*)

	P (mg/kg)						
PG	5	10	15	20	25	30	35
0.05	EST	EST	EST	EST	EST	EST	EST
0.10	EST	EST	EST	EST	EST	EST	GR0
0.15	EST	FGR0	FGR5	FGR5	GR5	GR5	GR5
0.20	FGR5	FGR5	FSR5	FGR5	FGR5	FGR5	GR5
0.25	FGR5	FGR5	FGR5	FGR5	FGR5	FGR7.5	GR7.5
0.30	FGR5	FGR7.5	FSR7.5	FGR7.5	FSR7.5	FGR7.5	SR7.5
0.35	FGR7.5	FGR7.5	FGR10	FGR10	FGR10	FGR10	GR10
0.40	FGR7.5	FGR10	FGR10	FGR10	FGR10	FGR10	GR12.5
0.45	FSR7.5	FGR10	FGR12.5	FGR12.5	FGR12.5	FGR12.5	GR12.5
0.50	FSR10	FSR12.5	FSR12	FGR15	FGR15	FGR15	GR15
0.55	FSR10	FSR12.5	FSR15	FSR15	FSR15	FSR15	SR15
0.60	FSR12.5	FSR15	FSR15	FSR15	FSR15	SR15	SR15
0.65	FSR12.5	FSR15	FSR15	FSR15	SR15	SR15	SR15
0.70	FSR12.5	FSR15	FSR15	FSR15	SR15	SR15	SR15
0.75	FSR15	FSR15	SR15	SR15	SR15	SR15	SR15
0.80	FSR15	SR15	SR15	SR15	SR15	SR15	SR15

3.2.2 Financial benefits of tactical grazing rest

The model was solved for two scenarios; "with" and "without" tactical grazing rest strategies. Reported are the financial benefits in terms of net present value (NPV) and the change in the composition of perennial grasses over a 20-year simulation period. For this analysis it was assumed that the initial level of soil *P* was not a constraint to production (i.e. $P_1 = 30$).

The NPVs were derived from simulations of the model for a range of initial *PG* values for the two scenarios. The economic value of the tactical grazing rest strategy was obtained by calculating the difference in the NPV for the "with" and "without" scenarios and expressing the result as a percentage (Figure 2). This indicates that the maximum benefit, an increase in NPV of 18%, due to access to tactical grazing rests occurred for *PG* values of around 0.20. At *PG* values less than 0.20 the benefits of grazing rests become marginal given that there is an alternative strategy of pasture establishment. For initial *PG* values greater than 0.20 the benefits of tactical grazing remained greater than 10%.

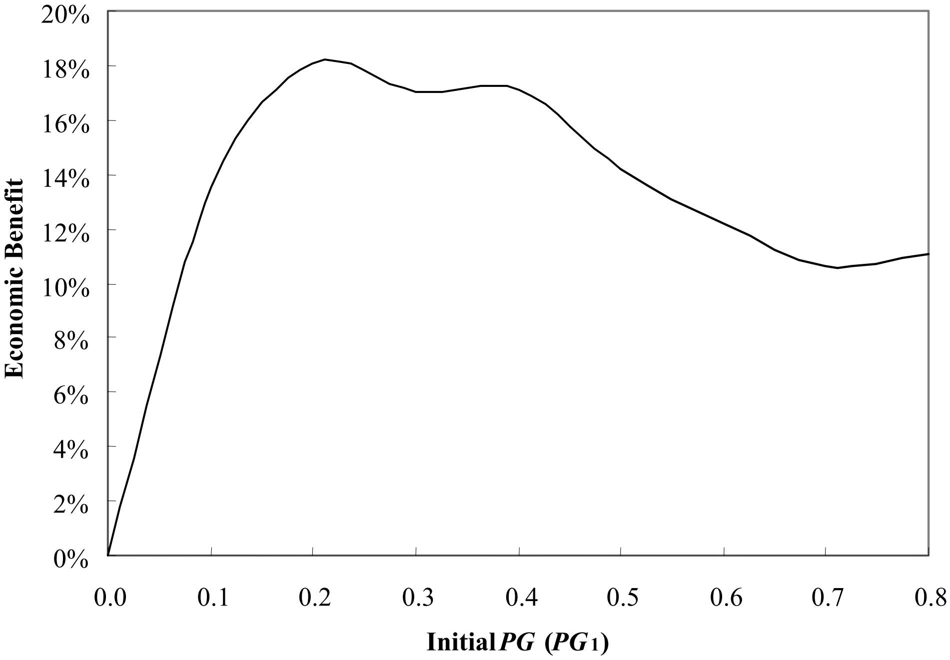

Figure 2. Financial benefit from tactical grazing rests

The annual perennial grass composition over the 20-year simulation period associated with the two scenarios and an initial value of *PG* of 0.20 is illustrated in Figure 3. The adoption of the tactical grazing rest technique resulted in a substantially greater rate of increase in the perennial grass composition, increasing from 0.20 to 0.50 within 5 years. Also, the optimum value of *PG* was greater for the "with" grazing rest scenario. Whereas continuous stocking (i.e. "without" grazing rest) resulted in an optimum value of *PG* of around 0.35 with occasional peaks of 0.40, the "with" grazing rest strategy maintained *PG* between 0.40 and

0.50. The average perennial grass composition on the Central Tablelands is presently around 20 to 30% (Dellow *et al.*, 2002). Thus, substantial adoption of the grazing rest strategy by farmers could potentially result in a large increase in the perenniality of grazing systems.

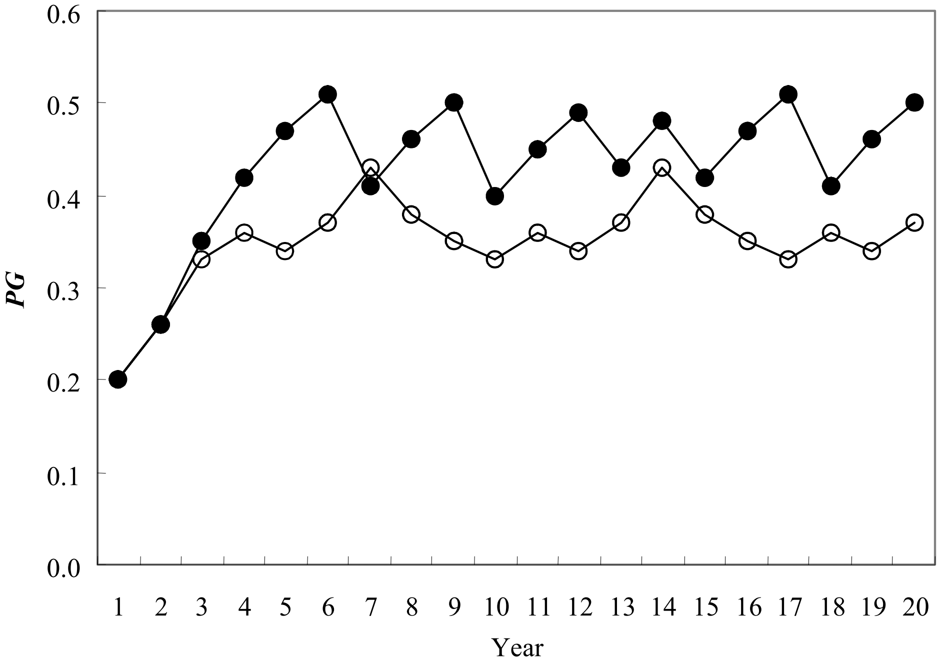

Figure 3. Change in perennial grass composition (*PG*) over a 20-year simulation for "with" (●) and "without" (○) grazing rest scenarios for an initial *PG* of 0.20

3.3 Accounting for externalities and public benefits of perennial grazing systems

The social or public benefit and costs were assessed by accounting for the externalities of grazing management by introducing non-zero values for the environmental variables and by including the strong sustainability constraint. The analysis reported above assumed that deep drainage to the watertable, runoff to stream systems and soil loss have no economic value and thereby reflect only the private benefits from grazing management. The public benefit analysis was replicated for both soil types, but only the kurosol soil results are reported due to the similarity of the outcomes. Because the unit value of the external costs and preservation benefits have not been identified from prior research, a parametric approach was taken whereby a range of values for P_{DD}, P_{RO}, P_{SL} and B_P were used.

3.3.1 Polluter-pays approach

The impact of various external cost values upon *DD*, *RO*, *SL*, NPV and the steady state perennial grass composition (PG_{ST}) are presented in Table 9. In each case of varying the external cost values P_{DD}, P_{RO} and P_{SL}, there was little impact upon the optimal decision rule and, consequently, the results for *DD*, *RO*, *SL* and PG_{ST} were insensitive to the size of the external costs. However, the inclusion of an external cost had a substantial negative effect upon the economic returns over the 20-year simulation period as reflected by the decline in NPV.

Table 9. Average annual deep drainage (*DD*), runoff (*RO*), soil loss (*SL*), steady state perennial grass composition (*PG*) and net present value (NPV) on a kurosol soil for various external cost values (P_{DD}, P_{RO}, P_{SL})

	DD (mm/ha/year)	*RO* (mm/ha/year)	*SL* (t/ha/year)	PG_{ST}	NPV ($/ha)
P_{DD}					
0.0	204	na	na	0.51	1154
0.2	204	na	na	0.51	617
0.4	204	na	na	0.51	94
0.6	204	na	na	0.52	-446
P_{RO}					
0	na	3.6	na	0.51	1154
10	na	3.6	na	0.51	690
20	na	3.6	na	0.51	210
30	na	3.6	na	0.51	-263
P_{SL}					
0	na	na	0.65	0.51	1154
50	na	na	0.64	0.51	729
100	na	na	0.63	0.51	302
150	na	na	0.62	0.53	-117

na – not applicable

3.3.2 Beneficiary-pays approach

The preservation benefit was varied for values of B_P ranging from zero (the private optimum) to $500/ha. The value of PG_{ST} resulting from these simulations is plotted in Figure 4, which indicates that there was no change in the value of PG_{ST} from that of the private optimum for preservation benefits up to $200/ha. The optimal composition of perennial grass increased to around 0.75 once the value of B_P exceeded $300/ha.

3.3.3 Direct regulation approach

Various values of X_T, the terminal perennial grass composition, were evaluated to determine the impact upon *DD*, *RO*, *SL* and NPV (Table 10). This constraint implies that at any stage of the 20-year simulation, the value of *PG* cannot be less than the X_T. Due to the nature of the strong sustainability constraint it is meaningless to conduct a simulation where the initial perennial grass composition (i.e. PG_1) is less than X_T. Consequently PG_1 was set at 0.8 for each simulation for the comparisons to be meaningful. The results indicate there is a marginal decline in *DD* and *RO* as the value of X_T is increased. In the case of the kurosol soil, *DD* declined from 199 at $X_T = 0.4$ to 185 at $X_T = 0.7$ (a 7% decline), and *RO* fell from 3.5 to 3.0 (a 14% reduction).

The impact upon *SL* was more substantial, declining from 0.58 at $X_T = 0.4$ to 0.35 at $X_T = 0.7$ (a 40% reduction). Increasing the value of X_T had a negative impact upon the level of private benefits as measured by the NPV, which declined from $1419 at $X_T = 0.4$ to $674 at $X_T = 0.7$

(a 52% reduction). The unconstrained NPV of $1419 in Table 10 was greater than the unconstrained NPV of $1154 in Table 9 due to the higher initial *PG* value of 0.8.

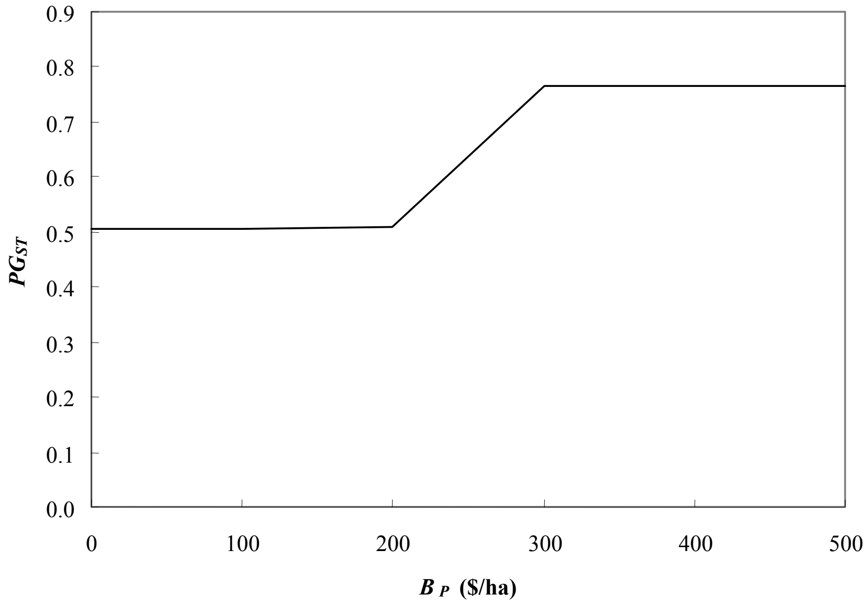

Figure 4. Change in steady state perennial grass composition (PG_{ST}) for various preservation benefit values of B_P

Table 10. Average annual deep drainage (*DD*), runoff (*RO*), soil loss (*SL*) and net present value (NPV) for various minimum perennial grass states (*XT*)

X_T	*DD* (mm/ha/year)	*RO* (mm/ha/year)	*SL* (t/ha/year)	NPV ($/ha)
0.4	199	3.5	0.58	1419
0.5	198	3.4	0.55	1379
0.6	191	3.2	0.46	977
0.7	185	3.0	0.35	674

4. Summary and Conclusions

This paper describes a framework for examining sustainability issues and the various interactions between desirable perennial and less desirable annual species in a grazed pasture. The concept of sustainability is discussed and a bioeconomic model is described for application to the problem along with its underlying assumptions.

A case study approach is used and the variables and their derivation described. These included grazing management decisions, the simplified process for allowing pasture species composition to vary over time, the creation of a soil fertility index based on Bray-phosphorus, the use of the PERFECT water model to monitor water fluxes, and a grazing systems simulation model to account for the pasture-livestock dynamics.

In a technical sense, the level of perenniality can be increased to 100% of a pasture composition (with consequent improvement in water and weed management) through improved pasture and grazing management (eg. summer grazing rests). Agronomically, pasture production requires the presence of legumes and an upper limit of around 70% perenniality. The results of this study suggest, that once the long-run benefits and costs of pasture are taken into account, a perennial grass composition of around 50% is optimal from a private individual's perspective. The opportunity costs involved in increasing perenniality from this level using either reduced stocking rates or tactical summer rests are not matched by future benefits from improved pasture quality. However, given that the current average level of perennial grass composition of 20% is significantly below this, it is concluded that summer grazing rests are an efficient strategy for improving the state of degraded pastures on the NSW Central Tablelands. It pays for landholders to increase the proportion of a perennial grass in a pasture if the composition is below around 50%.

If Catchment Management Authorities consider public benefits could be obtained from perenniality at levels greater than that determined optimal in this study then other policy options will be required. Three potential policy options were considered to assess the likely impact upon landholders decision behaviour; a polluter-pays approach (external costs internalised), a beneficiary-pays approach (preservation benefit paid), and a direct regulation approach (strong sustainability constraint). None of these options changed to any degree the optimal decisions or levels of deep drainage or runoff given the management strategies included in this study. Therefore, broader management options to deal specifically with the problems of excess water will need to be considered so as to obtain better environmental outcomes from grazing management in this environment. Such options may include trees and deep rooted perennials (eg. lucerne). To properly account for the responses and scale of benefits, a catchment level analysis may be more appropriate than the paddock scale that was used in this study. However, this analysis demonstrated that there opportunity costs to landholders of increasing perennials beyond the levels identified as optimal here so as to ameliorate environmental problems.

It is difficult to extrapolate the results from this case study to other environments with confidence due to differences in soil types, aspect, climate and suitability of different perennial species. In environments where there is a greater response in perennial grass composition to tactics such as grazing rests, it is probable that the optimal perennial grass composition may be higher. This is because the opportunity costs from grazing rests are reduced as the rate of change of perennials is increased. Likewise, the rate of perennial grass decline due to continuous grazing will influence the long-term optimal perennial grass composition. For instance, in environments where, due to the nature of the perennial grass species and livestock systems present, there is a slower degradation in perenniality due to grazing then the optimal level of perennials will be higher than estimated here.

In this study the effects on deep drainage, runoff and soil loss were determined from manipulation of the species composition of the pasture. It was found that, at the paddock level, there were reductions in the average annual values of these variables as the level of perennial grass is increased. However, the impact of the grazing rest technique did not have a major impact upon water dynamics due to the small difference in the economically optimal level of perennial grass calculated for the 'with grazing rest' and 'without grazing rest' scenarios. Although it is technically feasible to increase perennial grass composition to 80% or more, and thereby further reduce leakage of water from the root zone, imposing targets of perennial grass composition greater than 50% impose costs and are unlikely to be adopted by producers. Furthermore, the benefits in terms of improved environmental outcomes at the catchment-level may not be significant given the small differences in average deep drainage derived from the model for 50% and 80% perennial composition.

Although it is tempting to claim that certain strategies are more 'sustainable', we believe such a claim is inappropriate given the potential catchment and industry-wide impacts not considered from paddock based (experimental or model) studies. Moreover, there are often trade-offs between environmental outcomes and between the environment and other social goals in the pursuit of sustainability (Graham-Tomasi 1991, Pannell and Schilizzi 1999). For example, the foregone downstream benefits from dilution flows due to reduced high quality runoff may more than offset the long-term regional salinity benefits from reduced deep drainage. Following Graham-Tomasi (1991) sustainability should be considered as a broad set of concepts that guide research, and should not be considered a set of technologies that can be explicitly recommended for adoption. Paddock or property scale analyses such as reported here can quantify and value changes in the nature of environmental externalities due to policies or management actions and can make claims as to whether the problem is better or worse as a result – but no more. The concept of a sustainable production system should be viewed as a goal rather than some endpoint represented by a collection of technologies. Consequently, we can be confident from this study in stating that an increase in perenniality due to grazing rests generates positive production benefits and is likely to reduce negative environmental influences such as deep drainage and soil loss, but we are unable to conclude whether the adoption of such a technology will lead to a more sustainable agricultural production system at the landscape scale.

Investment in research that leads to more profitable perennial farming systems is likely to lead to public benefits as it may satisfy the needs of future generations my increasing wealth and reducing resource degradation (Mullen and Bathgate 2002). To further our knowledge of the implications for sustainability from grazing management requires a better understanding of the environmental impacts at a catchment level, and the effect of new technologies and farm decision-making on the catchment processes. This represents a logical extension for the paddock based framework presented in this study.

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