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The on-farm impact of alternative grazing management options to improve sustainability in western Chinese grasslands

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Abstract

Chinese grasslands are suffering considerable pressures from human and livestock populations. It has been estimated that 90% of Chinese grasslands are suffering from light to heavy levels of degradation. Allied to this is the low household income of herders and farmers dependant upon livestock products for their livelihood. Although a range of reasons have been proposed for the high levels of grassland degradation, principal among these are the high stocking rates adopted by farmers. This not only results in high utilisation rates of the pasture biomass, leading to bare areas and soil erosion, but individual animal productivity rates also decline. This paper presents the results of a modelling study of a grassland system in Gansu Province and Inner Mongolia Autonomous Region in northern China. This shows that reducing stocking rates leads to not only an increase in livestock productivity, but whole-farm returns are also increased. From a sustainability perspective, the greater pasture biomass remaining on the grassland also reduces the incidence of soil erosion in the areas.

Keywords: sustainable grazing, bioeconomic model, China.

1. Introduction

The area of grasslands in China is about 390 million hectares, which represents 41% of the total area of China (Nan 2005). About 70% of China's population of 1.3 billion people live in rural areas, and many of these depend upon grasslands for livestock production (Xu et al 2006). Consequently, the management and state of Chinese grasslands has important implications for China's welfare and productivity.

It is estimated that over 90% of Chinese grasslands are facing substantial degradation problems from overgrazing by livestock as evidenced by a reduction in grassland herbage mass, soil erosion and declining agricultural productivity. Moreover, the problem is worsening as evident by the area of degraded grasslands in China expanding at a rate of 2 million hectares a year. This is equivalent to 0.5% of the current total grassland area. Desertification of grazing areas is a particular problem in Inner Mongolia Autonomous

Region and Gansu Province due to a combination of management and changing environmental conditions.

There are two aspects to grassland degradation; the conversion of grassland to agricultural land and over-exploitation of existing grassland (Nan 2005). Due to increasing population pressures large areas of grassland have been converted to cropland over the past 50 years. Many of these areas are now highly degraded due to a combination of cultivation, lack of vegetation cover and strong winds, and are a major source of dust storms in northern China. There has been both a reduction in the size of the area of grasslands and a need for it to support more livestock to meet various policy initiatives (Wang and Ripley 1997). As the grassland environment has worsened the quantity and quality of high quality grasses and legumes has declined, leading to deterioration in the economic viability of these areas. Combined with a reduction in herbage mass and enhanced wind erosion of the top soil, the future ecological and economic viability of many grassland areas is questionable.

Inner Mongolia has been one of the most rapidly growing regions in China for the past 50 years. This development has resulted in significant areas being cleared for crops, and the remaining grassland area kept in livestock production has become overgrazed. Inner Mongolia now has a significant problem with wind erosion in winter and spring when strong winds pass through from Siberia towards the Pacific. The on-site consequences of this soil erosion are nutrients being lost when soil particles are blown downwind, reducing soil productivity. The off-site impacts occur from the soil particles being carried long distances. Commonly cited examples of the impact of dust storms in cities such as Beijing and Tokyo include loss in visibility, soil deposition on buildings and infrastructure, and a range of human illnesses such as respiratory diseases (Wang et al 2002).

This paper presents a component of an Australian Centre for International Agricultural Research (ACIAR) funded project (Sustainable development of grasslands in western China: ACIAR LPS/2001/094). The focus here is to present a bioeconomic modelling framework developed to evaluate the impact of alternative livestock management systems upon grassland biomass, soil erosion, soil depth, soil fertility, and economic returns. The model is used to evaluate the impact of different stocking rates and the potential for adopting a tactical grazing management system. The results presented in this paper should be viewed as preliminary in nature, as further effort is required to improve local data and to validate various functional relationships included in the model.

2. The case-study region

The case-study area reported here is Siziwang Banner in Inner Mongolia Autonomous Region in northern China (Figure 1). Siziwang lies approximately 150 km north of Hohhot, the capital of Inner Mongolia, and is generally described as ‘desert steppe’ in terms of climate, vegetation and terrain. The climate can be extreme and is typified by a short growing season over summer, an average annual rainfall of 315 mm and dry, cold periods from autumn through to spring with temperatures often below –20°C. Mean annual temperature is 3.5°C (Figure 2), and the altitude is 1500m. Animal productivity is often poor, and in some years mortality rates can be high due to extreme weather conditions.

Figure 1. The location of the case study area in northern China

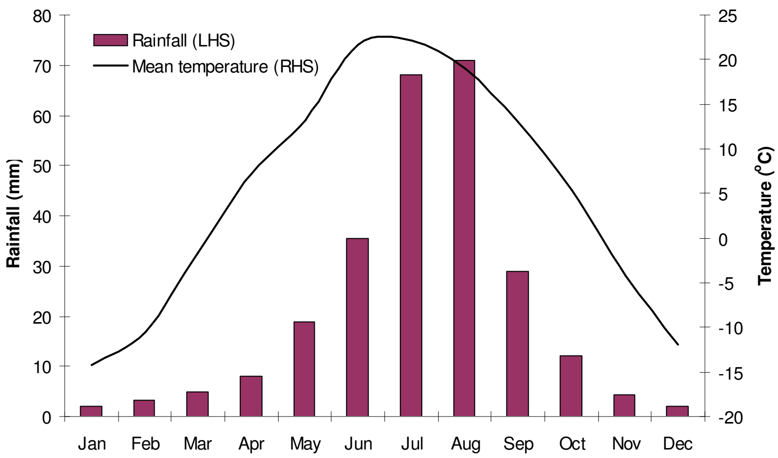

Figure 2. Mean monthly temperature and precipitation for Siziwang Banner, Inner Mongolia

Farms in Siziwang are large by Chinese standards, averaging around 500 ha with most used for livestock grazing. There is very little crop or forage production, although small areas of maize (less than 1 ha) can be irrigated from wells. Supplementary feed is commonly mixtures of maize residue and grain, usually purchased from off-farm, however, there is some production of meadow hay. Common grazing is the usual practice in Chinese grasslands, however in this area of Siziwang farms have assigned rights (i.e. they have individually allocated areas of land), though the fencing is usually not entire nor adequate to stop straying stock. The main livestock enterprises are sheep and goats which are grazed for meat, coarse wool and cashmere production.

The soil type is largely sand to sandy loam, and is highly susceptible to wind erosion. Encroachment of the Gobi Desert through desertification is a particular problem in Inner Mongolia, and is attributable mostly to a loss of vegetation through overgrazing.

3. A theoretical biological framework for reducing stocking rate

Jones and Sandland (1974) presented a framework for understanding the relationships between stocking rate and animal productivity. The authors examined data from a number of grazing experiments and demonstrated that animal productivity, as measured by gain per animal (Figure 3), declined linearly with increasing stocking rate. Production on an area basis was shown to rise with increasing stocking rate, and to then decline as the loss in per animal production exceeded the gain from increasing livestock numbers.

Jones and Sandland defined an optimal stocking rate being the rate that maximised production per hectare. They were able to show that a quadratic relationship applied for the gain per hectare, and presented the relationships between gain per animal (Y_a) and gain per hectare (Y_h) as follows:

$$Y_a = 1.999 - 0.999x$$
$$Y_h = 1.999x - 0.999x^2$$

Where x is the ratio of stocking rate to the optimal stocking rate (Figure 3). From these equations it is apparent that the linear model predicts that gain per animal at the optimum stocking rate is half that at infinitely low stocking rates. In Chinese grassland systems it is likely that stocking rates adopted are considerably greater than the optimum stocking rate identified in Figure 3. This results in substantially lower rates of animal productivity than may be obtained with more conservative livestock management. The research question then involves understanding the trade-off in increased productivity per animal versus a reduction in the number of animals to identify the quadratic in Figure 3.

The use of the term ‘optimum’ stocking rate by Jones and Sandland is misleading as it simply represents the point of maximum livestock productivity in terms of animal gain per hectare and does to indicate any ‘economic optimum’. In addition, when the effects of long-term grassland degradation are included, the identification of the ‘economic optimum’ stocking rate may be significantly lower than would otherwise be the case in a static framework. Nevertheless, the Jones and Sandland concept is useful as it provides a biological productivity case for reducing stocking rates.

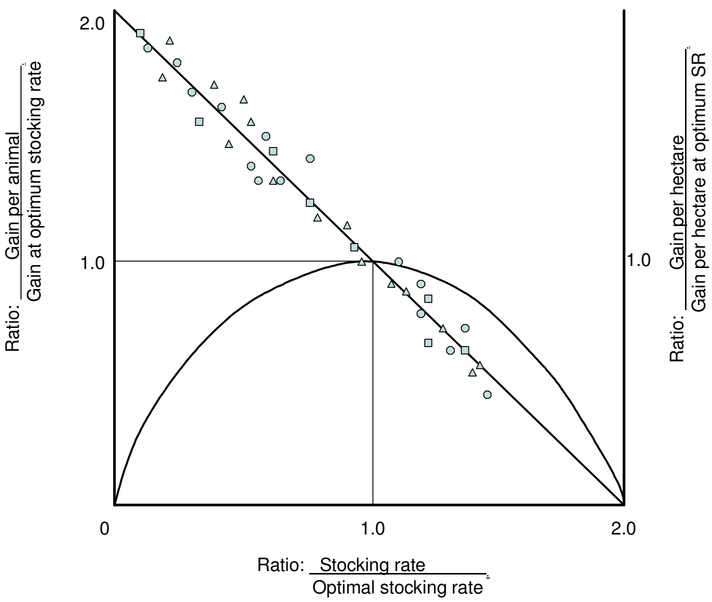

Figure 3. The relation between stocking rate and both gain per head and gain per hectare. Source: Jones and Sandland (1974).

4. Model framework

A bioeconomic modelling system was developed to evaluate alternative livestock management options in northern China grasslands. This follows the framework presented by Pandey and Hardaker (1995) for including the inter-temporal tradeoffs for a sustainability problem.

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

subject to

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

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

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, 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.

For the sustainable grasslands problem three inter-temporal states of nature are identified; the maximum annual biomass of grassland production, the carryover of grassland herbage mass, and the soil depth. The measure of maximum biomass achievable represents the grassland condition and is used as the carrying capacity, or asymptote, in a pasture growth equation.

The level of herbage mass of the grassland is an important determinant of livestock production and degree of soil erosion. The growth of new herbage mass (daily or monthly) is a function of the grassland biomass carrying capacity, soil fertility and the existing biomass. Hence, the carryover of herbage mass is important to derive the starting value for monthly growth rate. The soil depth variable is used to account for the cumulative effects of soil erosion upon soil fertility, and consequently on pasture growth. This is a dynamic relationship as soil erosion is directly influenced by herbage mass along with weather conditions and the soil properties.

The main decisions governing sustainable grassland resource use involve choice of livestock enterprise, the stocking rate and supplementary feeding strategy. The main livestock enterprise in the Siziwang study area is Mongolian fat tail sheep, which are a specialised mutton sheep breed. Merino sheep and goats are also produced in Siziwang Banner, however, there are few sustainability advantages in changing the livestock system. Consequently, in this study the two key decisions varied are stocking rate (defined in terms of breeding ewes per hectare) and the level of supplementary feeding (defined in terms of kilograms of supplement fed per animal per day). Pen feeding is another management strategy to reduce stress on the grassland, whereby livestock are kept indoors and fed solely on supplements during winter and early spring. This allows greater herbage mass to be maintained on the grassland thereby reducing the potential for soil erosion and resulting in higher spring pasture growth rates. The potential effect of pen feeding can be simulated by increasing the supplement feeding ration over these months and thereby satisfying livestock energy needs so that no grassland resource is utilised.

A monthly time step is used to calculate pasture growth, livestock energy demands, pasture intakes, and changes in animal body weights. Livestock productivity in terms of adult sheep body weights and lamb weight gain is a function of the quantity and quality of the grassland resource.

4.1 States

Grassland condition

A grassland condition (GC) state variable is defined to represent the change to grassland quality over time. This variable is the maximum herbage mass that can be produced within a growing season and is used as the asymptote in a pasture growth equation. It thus directly determines the rate of growth and herbage mass that can be achieved from the grassland. The change in grassland condition (ΔGC) is a function of its intrinsic growth and the harvest of the grassland condition (H) through the intensity of grazing by livestock. Consequently, this state can be represented by a resource-harvest model (Clark 1990).

$$GC_{t+1} = GC_t + \Delta GC_t - H_t \quad (4)$$

Soil depth

The level of soil fertility is likely to influence the rate of change in the condition of the grassland as well as the growth of herbage mass. Soil fertility is a function of soil depth, which itself is a function of soil loss as a result of wind erosion. The soil depth state variable (SD) is derived from Equation (5). We do not account for any increase in soil stock in this model.

$$SD_{t+1} = SD_t - \Delta SD_t \tag{5}$$

Grassland herbage mass carryover
The grassland herbage mass carryover (*HC*) variable is simply the final grassland biomass mass (*B*) derived for the final month of the previous year and is given by:

$$HC_t = B_{t-1(i=12)} \tag{6}$$

This variable is used in the calculation of the initial pasture growth rate and as part of a vegetative cover variable in the wind erosion equation.

4.2 Decisions

There are two key decisions; the stocking rate (*SR*) of sheep on the grassland over the summer months (breeding ewes/ha), and the level of supplementary feeding (*SF*) to adult sheep and lambs in each month (kg/head/day). Stocking rate is varied from 0 to 1 ewe/ha, while supplementary feeding in a grazing system is restricted to standard district practices of around 1 kg/day in the winter months.

Two grazing management strategies are evaluated; continuous stocking and tactical grazing. For the first strategy the stocking rate is fixed regardless of grassland condition for the simulation period at rates of 0, 0.25, 0.75 and 1.00 ewes/ha. Under tactical grazing management the stocking rate is varied according to grassland condition around a defined threshold (*GT*). Below this threshold a conservative stocking rate is adopted, and above this threshold more intensive utilisation of the grassland by livestock can occur. The following tactical grazing options were evaluated by the model, where the first parameter is the stocking rate below *GT* and the second parameter is the stocking rate above *GT*; 0.00:0.25, 0.00:0.50, 0.25:0.50, 0.25:0.75, and 0.50:0.75.

An option to reduce grazing pressure on the grassland in winter months is to pen feed animals on supplements only, with no access to the grassland. This can have two potential outcomes; first, by maintaining greater herbage mass through winter the propensity for wind erosion in spring is reduced and, second, the combination of a higher quality ration and the reduction in cold stress from winter grazing can improve animal productivity. This productivity gain can be expressed as higher ewe body weights and accompanying fecundity.

4.3 Profit function

The profit function in the model represents the net farm income (π) from the livestock activities, being the difference between livestock income (Y_L) and livestock costs (C_L).

$$Y_L = L_{PRICE} L_{SOLD} L_{WEIGHT} + E_{PRICE} E_{SOLD} + W_{PRICE} W_{SOLD} \tag{7}$$
$$C_L = E_{VC} TEWES + L_{VC} TLAMBS + S_{COST} TSUPP \tag{8}$$
$$\pi = Y_L - C_L \tag{9}$$

Where L_{PRICE} is the price of lambs (¥/kg), L_{SOLD} is the number of lambs sold, L_{WEIGHT} is the liveweight of lambs (kg/head), E_{PRICE} is the ewe sale price (¥/head), E_{SOLD} is the number of ewes sold, W_{PRICE} is wool price (¥/kg), W_{SOLD} is amount of wool sold (kg), E_{VC} is the variable cost per ewe (¥/head), *TEWES* is the total number of ewes on hand, L_{VC} is the variable cost of lambs (¥/head), *TLAMBS* is the total number of lambs, S_{COST} is the cost of supplementary feed (¥/kg), and *TSUPP* is the total amount of supplement fed for the year (kg).

The study assumes that a farmer aims to maximise the present value (NPV) of net farm income over the planning horizon (*T*).

$$NPV = \sum_{t=0}^{T} \frac{\pi}{(1+\beta)^t} \tag{10}$$

Where β is the discount rate.

4.4 Biophysical model

A number of biological factors are required to be calculated so as to measure the transitions in the biological states and to estimate the production parameters for the profit function. The biological model that derives these parameters is now described. The main components of the biological model are a livestock sub-model, a grassland production sub-model and a soil sub-model. A monthly time step is used for the biological model.

Livestock sub-model
The number of ewes is a function of the stocking rate decision, the farm area (*AREA*) and the number of replacement ewes kept on hand (*REPL*).

$$EWES_t = AREA \cdot SR_t \tag{11}$$
$$REPL_t = EWES_t (RF + MORT) \tag{12}$$
$$TEWES_t = EWES_t + REPL_t \tag{13}$$

Where *MORT* is the mortality rate of adult sheep and the *RF* is the replacement factor, being the proportion of the ewe flock sold as aged sheep. The number of lambs sold is largely determined by the weaning rate (W_{RATE}), which is influenced by the ewe body condition (*BC*).

$$W_{RATE} = -0.89 + 3.7BC - 1.8BC^2 \tag{14}$$
$$BC = \frac{LW_i}{SRW} \tag{15}$$
$$L_{SOLD} = EWES \cdot W_{RATE} - REPL \tag{16}$$

Where *SRW* is the standard reference weight (kg) of adult sheep of a specific breed type. The supplementary feed decision on a monthly basis (kg/head/day) applies separately to ewes (S_{EWE}) and lambs (S_{LAMB}). The total supplement fed is:

$$TSUPP = \sum_{i=1}^{12} 30\left(S_{EWE\,i} \cdot TEWES + S_{LAMB\,i} \cdot TLAMBS\right) \tag{17}$$

The amount of wool sold (W_{SOLD}) is a function of wool cut per head (W_{CUT}) and the number of sheep shorn. A simple polynomial equation is used to estimate W_{CUT} as a function of ewe liveweight (*LW*).

$$W_{CUT} = 12.2 - 1.2LW + 0.04LW^2 - 0.0004LW^3 \quad (18)$$

The weight of animals (ewes and lambs) is calculated on a monthly basis, being a function of the previous month weight and change in liveweight (*LWG*). If intake of metabolisable energy is greater than energy needs then weight gain is positive, while if energy intake is less than maintenance energy needs animals lose weight as energy demand is met from body reserves (i.e. tissue or fat). The calculation of liveweight gain or loss follows that of CSIRO (2007).

$$LWG = 30\frac{ER}{0.92EVG} \quad (19)$$

$$EVG = 6.7 + R + \frac{20.3 - R}{1 + \exp[-6(BC - 0.4)]} \quad (20)$$

$$R = \frac{MEI}{ME_m} - 2 \quad (21)$$

$$ER = 0.043 \cdot MD(MEI - ME_m) \quad (22)$$

$$MD = \frac{MEI}{DMI} \quad (23)$$

$$MEI = ME_g DMI_g + ME_s DMI_s \quad (24)$$

$$DMI = DMI_g + DMI_s \quad (25)$$

Where *ER* is energy retained by animal as body tissue (MJ), *EVG* is the energy content of empty weight gain (MJ/kg EBG), *R* is an adjustment for weight gain or loss, *BC* is body condition, *MEI* is the intake of metabolisable energy (MJ ME/head), ME_m is the maintenance energy demand of the animal (MJ ME/head), *MD* is the average metabolisable energy of animal intake (MJ ME/kg), *DMI* is total dry matter intake (kg/head), DMI_g is dry matter intake of grassland (kg/head), DMI_s is dry matter intake of supplement (kg/head), ME_g is the metabolisable energy level of grassland (MJ ME/kg), and ME_s is metabolisable energy of supplement (MJ ME/kg). Maintenance energy demand is derived from CSIRO (2007, p19).

$$ME_m = \frac{0.26LW^{0.75}\exp(-0.03A)}{k_m} + 0.09MEI + ME_{graze} + E_{cold} \quad (26)$$

Where *A* is animal age (months), k_m is efficiency of energy utilisation, ME_{graze} is additional energy required for grazing, and E_{cold} is additional energy required for cold stress. Compared to Australian grazing systems, the additional energy required for grazing and cold stress can be significant in northern China because of the distance sheep are herded combined with low biomass levels and the low winter temperatures experienced. Further detail of the calculation of ME_{graze} and E_{cold} is given in CSIRO (2007).

The maximum potential intake of a grazing sheep (I_{max}) is a function of its potential demand for energy and its physical capacity for feed intake.

$$I_{\max} = 0.04 \cdot SRW \cdot Z(1.7 - Z) \cdot CF \quad (27)$$

$$CF = \frac{RC(1.5 - RC)}{0.5} \quad (28)$$

$$RC = \frac{LW}{SRW} \tag{29}$$

$$Z = \min\left(\frac{N}{SRW}, 1\right) \tag{30}$$

$$N = SRW - (0.9SRW)\exp\left(-0.47 \cdot A \cdot SRW^{-0.27}\right) \tag{31}$$

Where *Z* is the relative size, *CF* is condition factor, *RC* is relative condition, *N* is normal weight, and *SRW* and *A* are standard reference weight and age of the animal. Dry matter intake (*DMI*) is calculated as a function of I_{max} and the relative intake (*RI*), expressed as a value between 0 and 1.

$$DMI = I_{max} \cdot RI \tag{32}$$

A full description of the approach for calculating *RI* is given by CSIRO (2007, p213-220), and is not repeated here due to the complexity of the equations involved. However, it is important to note here that the impacts of selective grazing are accounted for in the calculation of relative intake. This is achieved by allocating pasture biomass across 6 digestibility pools, and estimating the consumption of biomass across these pools.

Grassland sub-model

The quantity and quality of the herbage mass of the grassland are important factors for livestock production, and thus financial returns. The growth of pasture biomass in each month (Δ*B*) is based on a sigmoid pasture growth curve proposed by Cacho (1993).

$$B_{i+1} = B_i + \Delta B_i - LC_i \tag{33}$$

$$\Delta B_i = GI \cdot FI_t \cdot \alpha\left[\frac{B_i^2}{GC_t \cdot FI_t}\left(\frac{GC_t \cdot FI_t - B_i}{B_i}\right)^{\gamma}\right] \tag{34}$$

$$LC_i = TEWES \times E_{INT\,i} + TLAMBS \times L_{INT\,i} \tag{35}$$

Where *LC* is total consumption of grassland by livestock in month *i* (kg), *FI* is the fertility index, *GI* is a growth index (Fitzpatrick and Nix 1975), *α* and *γ* are parameters of the sigmoid equation, and E_{INT} and L_{INT} are the grassland intakes by ewes and lambs as derived from above. The parameter values for *α* and *γ* were estimated by fitting the equation to grassland data collected in Siziwang Banner.

A logistic equation is used to estimate the intrinsic growth of the grassland condition state variable (*GC*).

$$\Delta GC_t = \rho \cdot FI_t \cdot GC_t\left(1 - \frac{GC_t}{G_{max} \cdot FI_t}\right) \tag{36}$$

Where *ρ* is the intrinsic growth parameter and *K* is the carrying capacity or asymptote on maximum grassland biomass.

The following exponential equation was used to calculate the harvest of grassland condition as a function of stocking rate (*SR*), where *σ* is a shape parameter in the exponential function.

$$H_t = \sigma \cdot SR_t \sqrt{GC_t} \quad (37)$$

Soil sub-model
The change in soil depth (ΔSD) is a function of the amount of soil erosion:

$$\Delta SD_t = \frac{E_t}{SW} \quad (38)$$

Where ΔSD is the loss in soil depth (cm), E is total soil erosion (t/ha) and SW is the soil weight (g/cm^3), calculated as follows:

$$SW = 100BD \quad (39)$$

Where BD is the soil bulk density (g/cm^3). The fertility index variable is represented by a simple exponential function which was parameterised on the basis of expert opinion.

$$FI_t = e^{-\phi SL_t} \quad (40)$$

Where SL is the cumulative soil loss (cm) from an initial depth of 1 metre and φ is a shape parameter. Wind erosion is the main cause of soil loss in Siziwang Banner, consequently the Wind Erosion Equation (WEQ) model (Woodruff and Siddoway 1965) is used here. There are various descriptions of the WEQ (Lal 1990; Skidmore 1988) and the basic equation is:

$$E = f(I, K, C, L, V) \quad (41)$$

Where f indicates relationships are not straight-line mathematical calculations, I is the soil erodibility index, K is the soil roughness factor, C is the climate factor, L is the unsheltered distance, and V is vegetative cover factor. The I factor is expressed as the average annual soil loss per year and accounts for the inherent soil properties that affect erodibility. These properties include texture, organic matter, and calcium carbonate percentage. The I factor is the potential wind erosion for an isolated, unsheltered, wide, bare, smooth, level, loose, and non-crusted soil surface. The K factor is a measure of the effect of ridges and cloddiness made by tillage and planting implements. In the case of a grassland system a value of K=1 is adopted. The C factor for any locality characterises climatic erosivity, specifically windspeed and surface soil moisture. The L factor considers the unprotected distance along the prevailing erosive wind direction across the area to be evaluated and the preponderance of the prevailing erosive winds. The V factor considers the kind, amount and orientation of vegetation on the surface. The vegetation cover is expressed in kilograms per hectare of a flat small-grain residue equivalent.

The values of I, K and L can be obtained from tables (USDA 2002) and published sources such as Hu et al (1995) for I, whereas values for C and V are more complex in their calculation. The climate factor is expressed as:

$$C = 34.48 \frac{v^3}{PE^2} \quad (42)$$

Where *v* is average wind velocity and *PE* is a precipitation-effectiveness index. The annual *PE* index is the sum of the 12 monthly precipitation indexes, expressed as follows:

$$PE = \sum_{i=1}^{12} 115 \left(\frac{P}{T - 10} \right)^{\frac{10}{9}} \tag{43}$$

Where *P* is average monthly precipitation (in) and *T* is average monthly temperature (°F). In deriving the vegetation cover factor the small grain equivalent (SG_e) is defined as a 10 inch long stalks of small grain, parallel to the wind, lying flat in rows spaced 10 inches apart, perpendicular to the wind. Various crops have been tested and their SG_e equivalents have been calculated (USDA 2002). For a grassland system the calculation of SG_e and *V* are as expressed as follows:

$$SG_e = \frac{1.6736 \cdot B_i^{1.1817}}{1000} \tag{44}$$

$$V = 1 - \frac{SGe}{SGe + \exp(0.48 - 1.32 \cdot SGe)} \tag{45}$$

5. Data

Data for parameterising the model was obtained from a range of sources including published information, field data and expert opinion. In the case of the intrinsic growth rate for the grassland condition state and the sigmoid growth curve parameters, experimental data was obtained from which parameters could be statistically estimated. For instance, Figure 4a illustrates the estimated logistic curve for grassland condition from a 20-year livestock exclosure experiment (Prof. Lieu, personal communication) in Inner Mongolia.

In the case of the sigmoid pasture growth equation parameters, experimental data of monthly pasture growth for Siziwang Banner was obtained along with climate data so as to derive a monthly growth index (*GI*). Estimated values for α and γ were then derived and the resulting fitted curve is plotted against actual data in Figure 4(b).

A number of functional relationships between various biological parameters and either grassland condition or livestock condition were derived from an expert consensus approach. A graphical representation of these functions for various parameters is given in Figure 5.

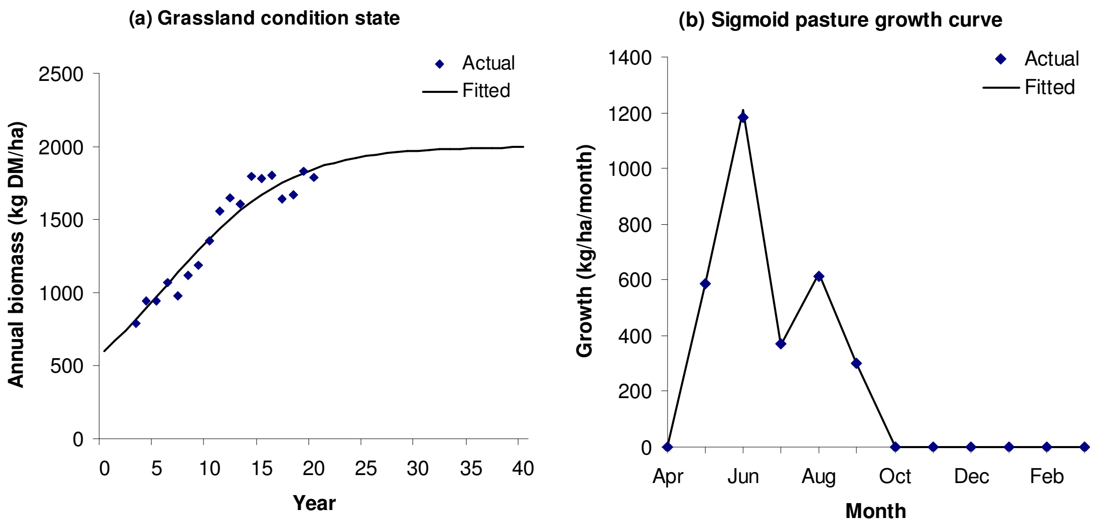

Figure 4. (a) Fitted logistic growth curve (–) to actual data (♦) of grassland condition response to livestock exclosure (Source: Prof. Liu, Inner Mongolia Agricultural University); (b) fitted sigmoid growth curve to Inner Mongolia pasture growth data

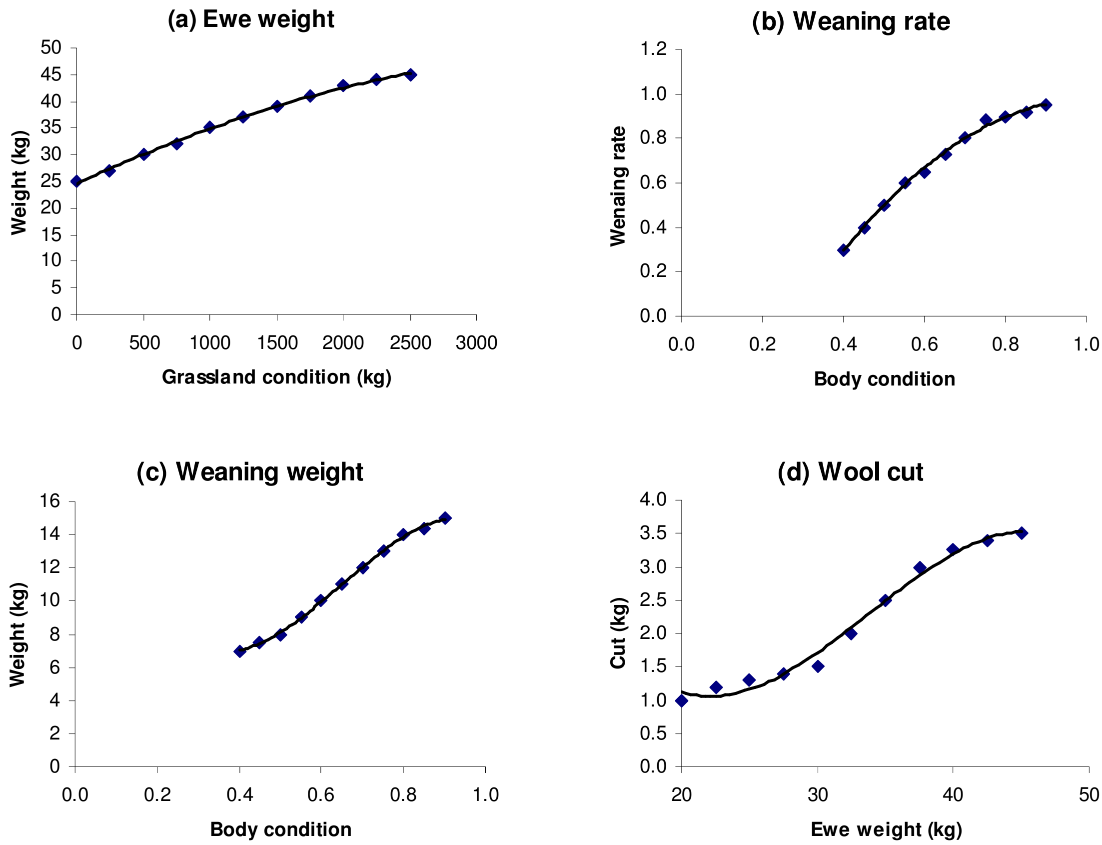

Figure 5. Derived functions for (a) initial ewe weight, (b) weaning rate, (c) weaning weight and (d) wool cut

Table 1. Data used in the model

Parameter	Unit	Value	Description
β	-	0.05	Discount rate
E_{PRICE}	¥/hd	200	Ewe price
L_{PRICE}	¥/kg	10	Lamb price (live weight basis)
W_{PRICE}	¥/kg	6	Wool price
E_{VC}	¥/hd	2.00	Ewe variable cost
L_{VC}	¥/hd	1.00	Lamb variable cost
S_{COST}	¥/kg	0.5	Supplement cost
T	years	50	Simulation period
A	months	24	Ewe age
SRW	kg	50	Standard reference weight
W_{AGE}	months	3	Lamb weaning age
S_{AGE}	months	8	Lamb sale age
S_{DDM}	%	75	Digestibility of supplement
$MORT$	-	0.02	Adult mortality rate
RF	-	0.20	Flock replacement factor
$AREA$	ha	200	Farm area
ρ	-	0.162	Intrinsic growth rate of grassland condition logistic equation
$G_{\max}$	kg/ha	3000	Carrying capacity of grassland condition logistic equation
σ	-	5.3	Exponential grassland harvest parameter
GT	kg/ha	1500	Grassland threshold
φ	-	0.035	Fertility index exponential parameter
BD	g/cm^3	1.3	Soil bulk density
I	ton/ac	193	Soil erodibility index
K	-	1	Soil roughness factor
L	-	1	Unsheltered distance

6. Results

6.1 Biological simulation results

The model was solved for each continuous and tactical grazing decision option for initial grassland condition values of 500, 1000, 1500, 2000 and 2500 kg/ha. This gave an extremely large set of results to potentially report on. For the sake of brevity in exposition, only a small set of these results is reported here.

Four of the key biological outcomes of the model are given in Figure 6 for the case of an initial grassland condition of 1000 kg/ha and a continuous stocking rate of 0.50 ewes/ha. This stocking rate decision was used as it does not result in a significant divergence of the grassland condition from the initial value over the simulation period. In this figure a number of percentiles (20^{th}, 50^{th}, 80^{th}) are presented for the monthly pasture growth derived from the sigmoid growth equation, the resulting herbage mass, and monthly weights of ewes and lambs up to the month of sale (S_{AGE}).

The pasture growth curves derived by the model (Figure 6a) show the short growing season experienced in this part of China. There is significant variability in monthly pasture growth, for example the maximum growth indicated by the 20^{th} percentile was 100 kg/ha whereas for the 80^{th} percentile maximum growth reached 600 kg/ha in July. There is concern regarding the representativeness of the model estimates of monthly growth due to a lack of quality field data to help parameterise the growth equation coefficients and to validate model outputs.

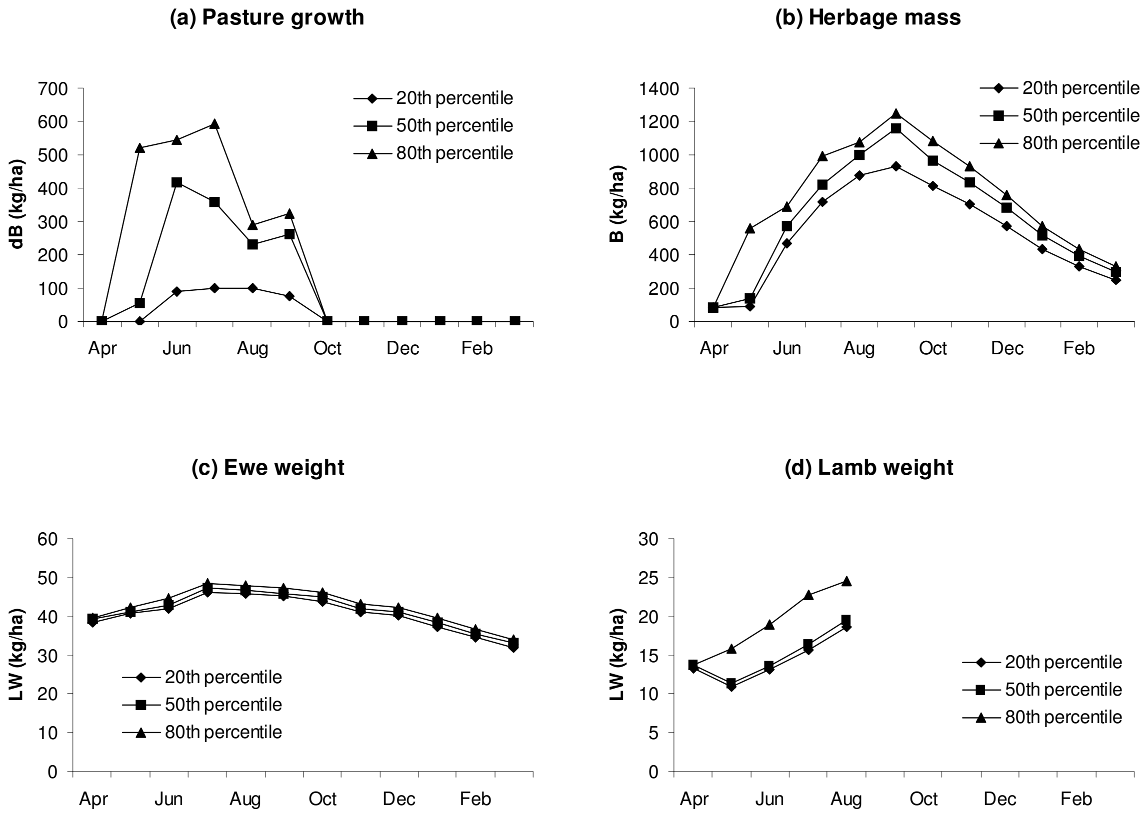

Figure 6. Model simulation results for (a) monthly pasture growth, (b) herbage mass, (c) ewe weights, and (d) lamb sale weight for the case of grassland condition of 1000 kg/ha and a stocking rate of 0.50 ewes/ha

The herbage mass results (Figure 6b) illustrate that the grassland biomass increases from extremely low levels in spring, reaching a maximum in September and then declines to low values over winter. This is consistent with experimental results and anecdotal evidence.

In this scenario ewe body weights increased over the summer months when pasture mass and quality were highest, and then declined over autumn and winter (Figure 6c). There was little difference in the monthly ewe weights between the 20th and 80th percentiles. The estimate of monthly lamb weights (Figure 6d) showed a range in values from 18 to 25 kg at the month of sale. This result is consistent with the expectations of local livestock specialists and farmers. Introducing supplementary feeding into the decision would likely result in an increase in lamb weights.

The impact of different initial grassland condition and stocking rate options are given in Figure 7 for the 50th percentile (i.e. the median) only. Increasing the initial grassland condition from 1000 to 2000 kg/ha has the anticipated effect of increasing both growth rate and herbage mass. However, it is interesting to note that increasing the stocking rate from 0.50 to 0.75 ewes/ha has a greater (negative) impact upon pasture growth than the initial grassland condition. Both pasture growth and herbage mass for the scenarios involving a 0.75 ewe/ha stocking rate (2000*GC*:0.75*SR* and 1000*GC*:0.75*SR*) were considerably lower than the scenarios with a 0.50 ewe/ha stocking rate. Both monthly ewe and lamb weights were also considerably lower for the higher stocking rate scenarios. This model result is consistent with the assertion of Jones and Sandland (1974) that animal productivity declines with increasing stocking rate.

Although the model outcomes appear plausible based upon local researchers experiences and expectations, more effort is required to develop greater confidence in the data inputs and model outcomes. In particular, we have concerns regarding the representation of grassland pasture growth (Figure 7a) given the poor data from this region on grassland growth. This problem is due to a combination of few experimental studies on seasonal growth, and the poor design or conduct of those studies that have collected grassland growth data. An alternative approach may be to parameterise a comprehensive pasture growth model, such as GrassGro (Moore et al. 1997), to estimate growth and herbage mass under a range of seasonal conditions and to then estimate the sigmoid parameters α and γ from this data.

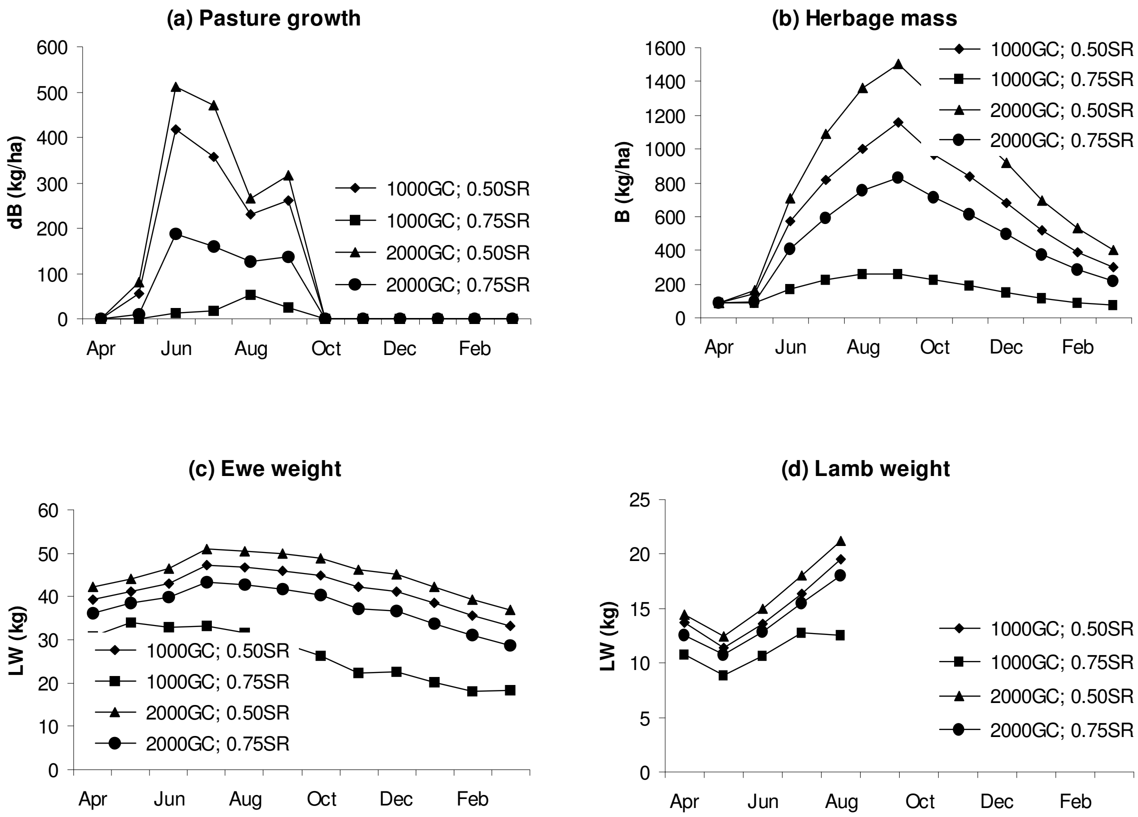

Figure 7. Median model results for (a) monthly pasture growth, (b) herbage mass, (c) initial weight and (d) lamb sale weight for various grassland condition and stocking rate conditions

6.2 Economic simulation results

The NPV from each continuous grazing and initial grassland condition scenario are reported in Table 2. For the lowest GC_0 value (500 kg/ha) a stocking rate of 0.25 ewes/ha was preferred (NPV $56079) to the other continuous stocking rate options. For initial grassland condition scenarios of 1000 and 1500 kg/ha the best continuous grazing option was 0.50 ewes/ha, whereas at the higher initial grassland condition states a continuous stocking rate of 0.75 ewes/ha was preferred on the basis of NPV.

Table 2. Net present value results for continuous grazing and tactical grazing options (¥)

	GC_0 500	GC_0 1000	GC_0 1500	GC_0 2000	GC_0 2500
Continuous grazing					
0.25 ewes/ha	56,079	87,571	100,891	106,958	109,001
0.50 ewes/ha	11,898	127,628	169,734	190,079	199,245
0.75 ewes/ha	-83,252	41,443	138,270	192,001	219,853
1.00 ewes/ha	-137,702	-43,477	51,763	120,219	162,960
Tactical grazing					
0.00 : 0.25	55,882	79,126	100,891	106,958	109,001
0.00 : 0.50	90,697	132,273	168,318	189,661	198,367
0.25 : 0.50	73,649	129,861	169,062	189,422	198,808
0.25 : 0.75	74,510	127,806	175,892	211,517	227,287
0.50 : 0.75	11,898	127,628	174,078	210,247	231,610

The results of the tactical grazing options are also reported in Table 2, with the option (continuous or tactical grazing) that gave the highest NPV being outlined. For all initial grassland conditions a tactical grazing option gave the highest NPV; 0.00:0.50 for GC_0 500 and GC_0 1000, 0.25:0.75 for GC_0 1500 and GC_0 2000, and 0.50:0.75 for GC_0 2500.

A range of biological outcomes from following these decision rules over the simulation period are derived by the model for each initial grassland condition state. Presented in Table 3 is the average annual soil loss from wind erosion over the simulation period for each of the continuous grazing options and the best of the tactical grazing decisions for that condition state. This clearly shows that as the initial grassland condition increases there is a consequent reduction in soil loss. However, more significant is the effect of increasing stocking rate regardless of the initial grassland condition, for example in the case of GC_0 1000 soil loss rises from 9.7 t/ha at 0.25 ewes/ha to 47.4 t/ha at 1.00 ewes/ha. Even in the case of GC_0 2500 large rates of annual soil loss (36.0 t/ha) can occur at the highest stocking rate.

Adoption of tactical grazing also has the potential to reduce soil loss (Table 3), as higher biomass values are achieved by this strategy. This is indicated by the temporal change in grassland condition for a number of grazing strategies (Figure 8a). If livestock were to be completely excluded then grassland condition would increase (from an initial state of 1000 kg/ha) to an asymptote of almost 2800 kg/ha within 20 years. However, utilisation of grassland ameliorates any improvement in grassland condition (stocking rates of 0.25 and 0.50 ewes/ha), and for stocking rates greater than 0.50 ewes/ha the grassland degrades further. The tactical grazing strategy results in an increase in grassland condition through the adoption of grazing rest, and condition is then maintained at around 1500 kg/ha.

Table 3. Average soil loss over the simulation period (t/ha/year)

	GC_0 500	GC_0 1000	GC_0 1500	GC_0 2000	GC_0 2500
Continuous grazing					
0.25 ewes/ha	11.4	9.7	9.4	9.3	9.3
0.50 ewes/ha	28.2	11.5	10.4	10.1	10.0
0.75 ewes/ha	51.0	36.5	26.0	21.1	18.9
1.00 ewes/ha	53.6	47.4	41.7	38.2	36.0
Tactical*	11.2	10.4	10.6	10.5	10.6

Tactical* is the best tactical grazing option for GC_0 state.

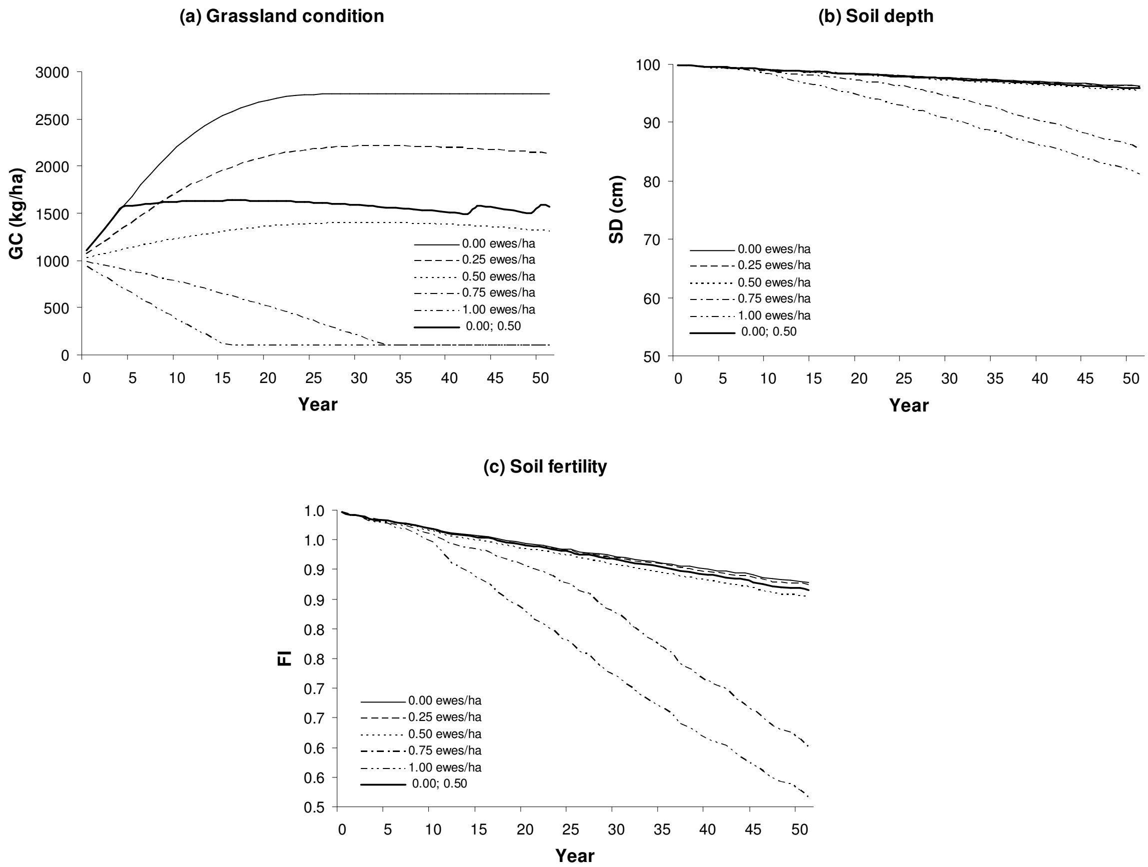

Figure 8. The temporal impact of alternative continuous and tactical grazing decisions on (a) grassland condition, (b) soil depth and (c) soil fertility index for the case of GC_0 of 1000 kg/ha

The impacts upon soil depth and the soil fertility index over the simulation period are illustrated in Figure 8b,c. This shows that at the highest stocking rates substantial degradation of the soil resource is likely to occur. In this case-study there is still some level of soil degradation at the most conservative stocking decisions, regardless of the initial grassland condition. This outcome is due to the high erodibility index of Siziwang soils and the low herbage mass values during periods of peak wind erosion in April and May (Figure 7b). In addition to the modelling of pasture growth the representation of soil erosion from the model requires further investigation and validation.

7. Discussion

This paper presented a bioeconomic modelling framework developed as part of an ACIAR funded project "Sustainable development of grasslands in western China: ACIAR LPS/2001/094" to assess the impact upon grasslands of alternative livestock management strategies. In addition to adopting a sustainability modelling framework, the analysis incorporates the Jones and Sandland (1974) concept of diminishing animal productivity as stocking rate increases. Important production parameters such as lamb weaning rates, lamb weaning weight and wool cut are all a function of ewe body weight or body condition. Ewe weight and condition is directly a function of the quantity and quality of pasture. High stocking rates impact upon pasture quality which then directly influences animal productivity.

The study adopted a simulation modelling framework using 52-years of weather data for Siziwang Banner in Inner Mongolia Autonomous Region. The key biological states tracked over time were the grassland condition, soil depth and the quantity of herbage mass carried over to the following year. The key livestock management decisions were the stocking rate, represented in terms of breeding ewes/ha, and the level of supplementary feeding. Two stock management options were considered, a standard continuous stocking rate system and a system based upon tactical grazing management. In the latter system, stocking rate varied depending upon the grassland condition around a pre-defined threshold.

The model was simulated for a number of initial grassland condition states, ranging from a maximum annual biomass production of 500 kg/ha to 2500 kg/ha, for each continuous and tactical stocking rate option. The highest economic returns measured over the simulation period were associated with a tactical grazing decision for each initial grassland condition. Tactical grazing also resulted in higher herbage mass and lower soil erosion rates than continuous stocking at the higher rates.

There are a number of limitations of this analysis that will require future attention. First, there are considerable concerns over the quality of some of the input data. In particular, there is insufficient experimental data on pasture growth rates with which to parameterise the sigmoid pasture growth curve used here. This problem may be overcome by utilising a more complex pasture growth model and applying it to this region. However, the problem of model validation will remain to some extent. Second, although this model includes the effect of variable seasonal conditions it is not truly a stochastic model. The next step will be to revise the model so that it can be solved as a monte-carlo simulation. Third, the model does not provide optimal decisions. One option may be to develop the framework using concepts of stochastic dynamic programming. Finally, there are a range of management and policy options for grassland management that may be included. These include the imposition of grazing bans, introduction of caps on stocking rates, and pen feeding to reduce grazing pressure on the grassland.

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