StageTHREE Sustainable Grasslands Model

Model description and users guide

A model developed as part of the ACIAR projects *LPS/2008/048 Sustainable Livestock Grazing Systems on Chinese Temperate Grasslands & ADP/2012/107 Strengthening incentives for improved grassland management in China and Mongolia*

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Downloading the *StageTHREE* model

The model is openly available as a Windows executable file (.exe) and requires pre-installation of Matlab Runtime which will occur during the installation process. A link to download the Windows application can be found here: https://www.aciar.gov.au/project/adp-2012-107

The *StageTHREE* Sustainable Grassland Model is also available as an open source program for researchers and analysts upon request. The base open source model requires a current version of Matlab to run, including the following Matlab tools: Statistics and Machine Learning, Financial Toolbox, and Curve Fitting Toolbox. To request a copy of the model or further information please contact Dr Karl Behrendt (email: kbehrendt@csu.edu.au).

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1 Introduction

Environmental, financial and political influences affect herders and farmers livelihoods with the expectation that they maintain biologically and economically resilient systems. Making decisions regarding the management of a grassland resource is an important and complex bioeconomic problem. It involves the consideration of interactions between grassland ecology, the use of technology to improve and manage the resource, environmental externalities, utilisation of the resource by grazing animals, and the profitability of the farming system.

Within any grazing system, decisions need to be made by managers and herders on how to best manage the existing mosaic of grassland resources available to them. This involves making decisions about how to utilise the existing resource through the adjustment of stocking rates and grazing management, or making decisions about the use of inputs and existing technologies such as fencing or labour to aid in the control of grazing, the application of fertilizer or manure, or the sowing of introduced species. The ultimate aim of the decisions being made is to improve farm profitability, household cash flows, animal production, grassland productivity, quality and persistence (Behrendt et al., 2013a; Kemp and Michalk, 2011; Scott et al., 2000). These represent a series of tactical and strategic decisions[5] that need to be made in a climate of uncertainty about their degree of success in achieving desired levels of production, profitability and environmental outcomes.

A grassland resource is dynamic in its response to utilisation and climate, and the impacts of decisions made at different points in time significantly influence profitability over the long term. Climate risk influences the future profitability and productivity of the grazing system, and the future state of the soil and grassland resource. The more recent approach to managing grassland resources is the continuation of a paradigm shift that occurred during the late 1980s and 1990s, to one where grasslands need to be managed as continually changing ecological systems. Kemp and Michalk (1994) defined grassland management as the process of actively intervening in the production of plants and their utilisation by grazing animals to maintain or

[5] Tactical decisions represent decisions made by producers to adjust their farming strategies in response to changes in seasonal and market conditions (Antle, J.M., 1983. Incorporating Risk in Production Analysis. American Journal of Agricultural Economics 65, 1099-1106.). Strategic decisions represent decisions made for the development of the business which involve inter-temporal benefits and costs (Rae, A.N., 1994. Intertemporal Activity Analysis, Agricultural Management Economics: Activity Analysis and Decision Making. CAB International, Wallingford, pp. 223-231.).

improve production while sustaining the resource. The options and technologies available to herders allows them to modify their management and utilisation of grasslands under stochastic climatic conditions. Hence grassland management includes the need to find a balance between grassland productivity and persistence, environmental outcomes, livestock production and whole farm profit.

The use of conventional production economics to support decision making regarding shorter term production and profit objectives of livestock grazing systems is unlikely to be viewed as acceptable to modern community values, where the focus is increasingly on improving environmental outcomes. The challenge lies in identifying profitable and ecologically sustainable livestock production systems from dynamic grassland resources (MacLeod and McIvor, 2006).

A greater realisation of environmental responsibilities over the past three decades has led to an increased emphasis on the development of sustainable grazing systems (Gramshaw et al., 1989; Humphreys, 1997; Hutchinson, 1992; Kemp and Dowling, 2000; Wilson and Simpson, 1994). A critical component to achieving sustainable grazing systems is one that is capable of sustaining high levels of productivity as well as meeting environmental objectives. In the case of Chinese grasslands, this relates to developing a grassland resource that is dominated by species capable of sustaining positive livestock production.

The complexity of the grazing and grassland system, and the need for it to be integrated within the farming system in a profitable and sustainable way, limits the usefulness of relying solely on field experimentation to obtain answers to the complex questions of sustainability in grassland systems. Modelling and simulation of complex farming systems provides the most efficient method of undertaking systems research to improve decision making (Bywater and Cacho, 1994). The development of bioeconomic models that consider the biophysical system and integrate dynamic grassland and soil resources, with livestock production and economic analysis provide a useful tool for finding sustainable solutions for grassland systems. Existing models and decision support tools such as GrazPlan suite of models (Donnelly et al., 1997; Moore et al., 2007) and the SGS Grassland Model (Johnson et al., 2003) are complex and require significant amounts of input and skill by users to create, calibrate and validate model outputs. In countries with limited modelling capacity and quantities of data in appropriate forms, parametrization of such complex models is difficult. These models are also constrained in the approaches that can be taken to simulating different innovations and the interactions of a stochastic climate with whole farm profitability and herder cashflows.

A suite of models has been developed and used to help understand the grazing systems and to investigate options for changes. The models have been used to identify possible changes in farm practice in China (Kemp and Michalk, 2011), Mongolia and Australia. The four models developed are: feed balance analyser (*StageONE*), linear program optimiser (*StageTWO*), dynamic sustainability (*StageTHREE*), and precision livestock management (*PhaseONE*). These models have been built as standalone units, but they share much common data and functions and are regarded as an integrated set (Figure 1.1), even though there are fundamental differences on time-step and planning horizon. The *StageTHREE* Sustainable Grasslands Model (SGM) is capable of running in a deterministic mode (a single year type being repeated), and stochastic mode (either a single run of randomly selected climate years or a selected number of iterations of randomly selected climate year sequences) to test a range of decision variables (such as flock/herd size, supplementary feeding rules, output price variability, management systems etc).

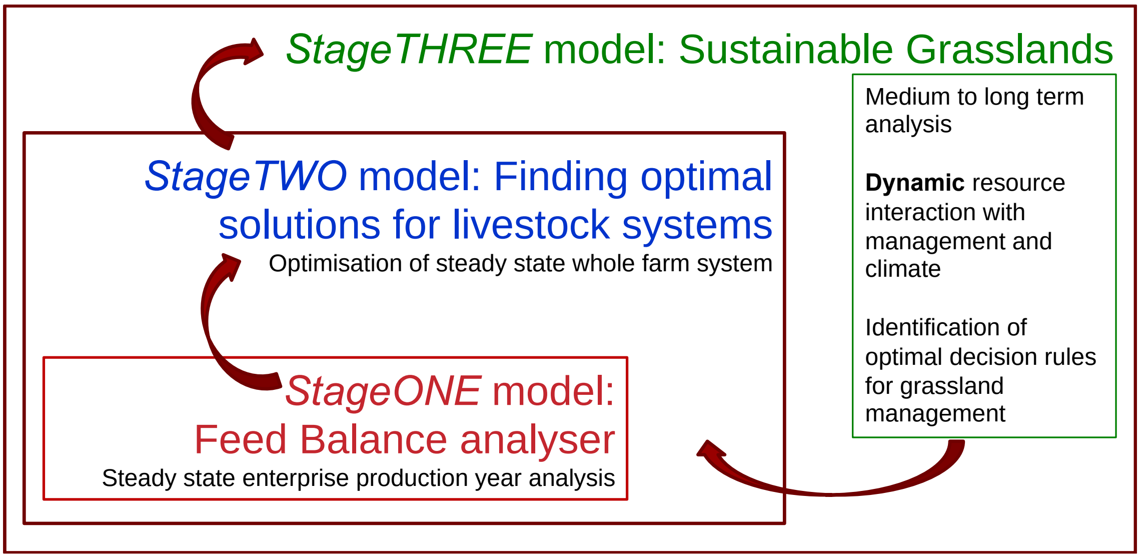

Figure 1.1: Integrated set of models, used for analysing the livestock / grassland system.

This manual introduces the *StageTHREE* Sustainable Grasslands Model which utilizes the core functions and dynamic dimensionality of more mechanistic tools, such as the GrazPlan suite and SGS Grassland Model, but has been designed to minimize the skill and data required for parameterisation. Additionally, the *StageThree* SGM runtime version has been designed to provide a range of commonly assessed measures of production, economic and environmental outcomes in response to pertinent questions (or decision variables) that are being considered for designing more sustainable Chinese, Mongolian and Australian grassland systems.

2 Sustainability modelling approach

The objective of this work was to develop a method that adequately models the dynamic nature of grassland resources and integrates climatic uncertainty. The method developed needed to be capable of identifying the inter-temporal trade-offs between the management of the grassland resource for herder household welfare and the resulting productivity and environmental outcomes from the grazing system.

The specific objectives of the model are to:

- To assess the impacts of different grassland management strategies on grassland condition, soil erosion, ecosystem services and herder household income,
- Analyse grassland management strategies over the medium to long term (10-50 years), and
- Account for the dynamic interaction of resource condition (grassland and soils) with management (livestock production system, stocking rate and supplementary feeding) and climate.

The bioeconomic framework that has been developed is unique in that it considers the impact of embedded climate risk, technology application and management on the botanical composition of the grassland resource over time, which, in turn, impacts on the economics and environmental outcomes of different strategies (Figure 2.1). It is a dynamic model of the interaction of resource condition (grassland and soils) with management (livestock production system (including sheep, goats, cattle and yak), stocking rate and supplementary feeding) and climate risk. The *StageTHREE* SGM operates as a simulation model that is executed for each nominated grazing area (field or paddock) level on a daily time step and contains 11 sub-models accounting for grassland dry matter digestibility (DMD); herd/flock structure, size and culling; supplementary feeding policies; growth, production and state variables for each age cohort of females, male progeny and breeding males; growth indices and grassland growth; deep soil water drainage and rainfall run-off; and soil erosion from wind and water run-off. Grassland composition and soil depth/fertility sub-models predict changes at an annual time step. Livestock production and system externalities (such as soil erosion and methane emissions from rumination) are aggregated to determine the environmental, economic and financial performance of the system at the enterprise and whole farm level.

The additional data required for the customization and running of the model above that is the *StageONE* and *StageTWO* models includes: soil fertility change over time and its interaction with soil erosion from wind and water; grassland growth and digestibility parameters; long term daily climate data (temperature, wind speed, precipitation, and relative humidity); dynamics of changes in grassland botanical composition under different management practices, soil conditions and climate; and livestock production in relation to grassland quantity and quality.

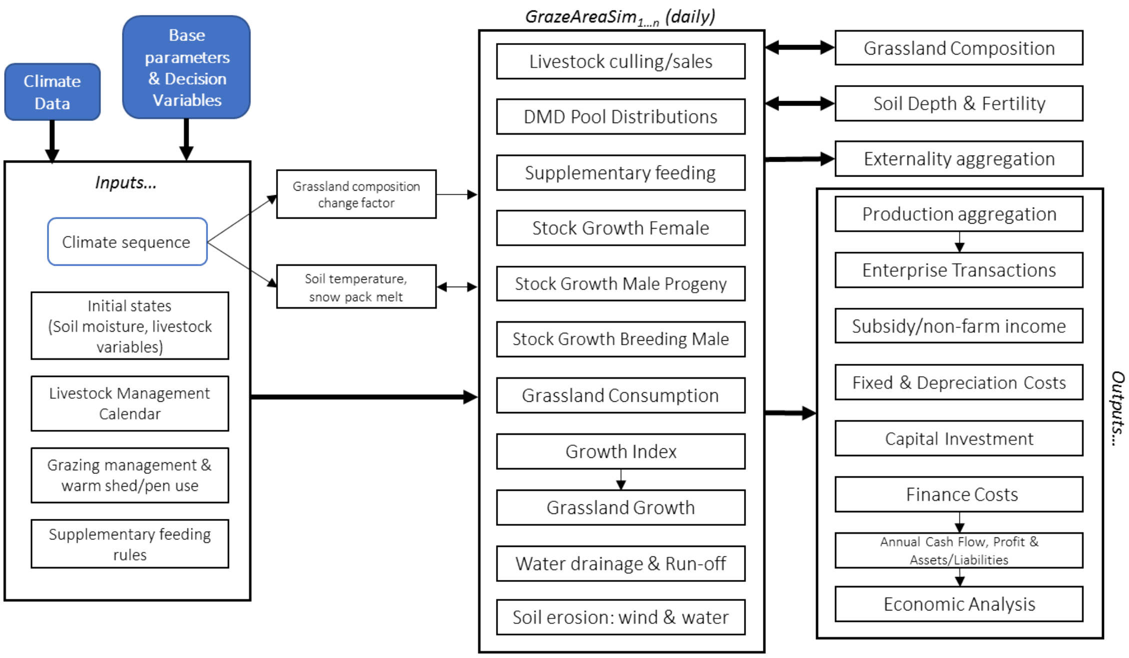

Figure 2.1: StageTHREE Sustainable Grasslands Model simulation framework.

The *StageTHREE* model is capable of running in several modes which should be used sequentially to calibrate and build confidence in model outputs:

1. Deterministic mode (a single year type being repeated for the user specified *Number of Years to simulate*) to initially investigate system stability and potential issues in set assumptions,
2. Deterministic mode which simulates each year in known sequence between nominated years (ideal for calibration against experimental or field data),
3. Single Stochastic run (a single run of randomly selected climate years) for the user specified *Number of Years to simulate* (ideal to ascertain and compare the expected range of possible outcomes and through inverse modelling derive reasonable estimates of initial states (Liu et al., 2009)), and
4. Full stochastic simulation mode (executed for a selected number of iterations of randomly selected climate year sequences using Monte Carlo simulation procedures) to test the impacts of a range of decision variables (such as flock/herd size, supplementary feeding rules, output price variability, management systems etc) on whole system performance.

The Monte Carlo sampling procedure within the model assume that price and climate variables are stochastically independent. However, for both the single stochastic and full stochastic mode, the random number generators used to determine the randomly drawn climate and price sequences are seeded to ensure all strategies (i.e. treatment levels) being tested utilise common random numbers and the same initial conditions. This is done to reduce the noise in the outputs (i.e. variance reduction) (Nakayama, 2008) and computational requirements.

The *StageTHREE* SGM has been developed using Matlab (Mathworks, 2019) and some specialised additional tools. This manual describes the runtime version that is available (Figure 2.2) and that can be used independent of the specialised software. This descriptive simulation framework can be used to investigate the expected production and environmental outcomes, and economic performance and risks associated with different technologies and grassland management policies over short to long term planning horizons (up to 100 years).

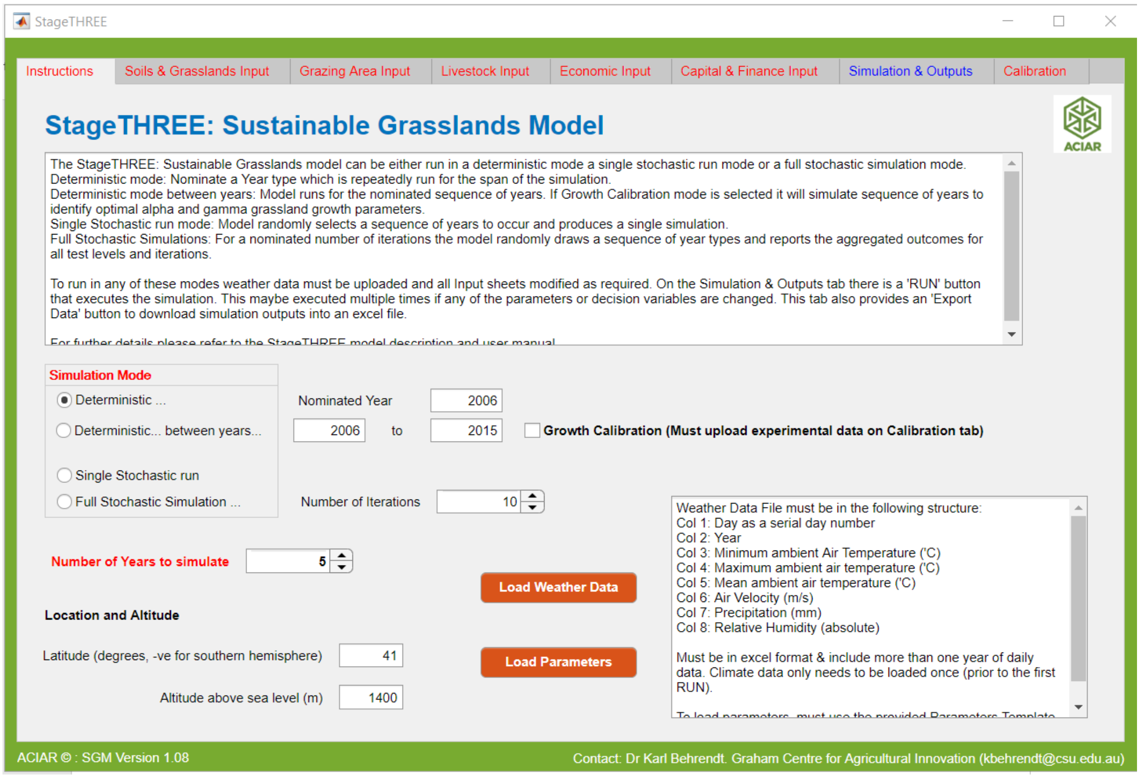

Figure 2.2: Runtime version of *StageTHREE* Sustainable Grasslands Model.

3 Model description

3.1 Modelling soil processes and erosion

The combined loss of soil through wind and water erosion processes have been determined through a combination of empirical and process-based models that utilise daily weather data. The estimation of wind erosion is based on a combination of a process-based model to determine saltation, and an empirical model to determine the vertical flux of dust emissions into the atmosphere. These are calculated using the process based models of Shao et al. (1996) and Lu and Shao (2001), and applied as adapted by Kang et al. (2011). The estimation of soil erosion due to rainfall runoff is modelled using the Revised Universal Soil Loss Equation as defined by Littleboy et al. (1999). The combined total loss of soil is expressed through changes in soil mass which is off-set by the rate of soil formation. The rate of soil formation relates to the amount of deep soil water drainage and is estimated using the method described by Wakatsuki and Rasyidin (1992) and utilises an approach of chemical weathering and mass balance accounting (Minasny et al., 2008). The ratio of soil mass to initial soil mass defines the soil fertility index which allows for soils to either increase or decrease in depth and fertility depending on the rate of soil mass change. In the model, the user may choose to turn off soil fertility dynamics. This will force the model to maintain the constant starting soil fertility index at 1.0 for the entire simulation period, and may be applicable to already eroded soils with generally limited Soil Organic Carbon in the higher soil horizons.

3.1.1 Soil fertility sub-model details

The ratio of soil mass to initial soil mass defines the soil fertility index which allows for soils to either increase or decrease in depth and fertility depending on the rate of soil mass change. The soil fertility sub-model is similar in nature to the concept of fertility scalars used in more complex biophysical models of grazing systems (Moore et al., 1997), but with the index limiting grassland growth at a daily time step as described in Cacho (1998). This occurs through the inclusion of FI_s in equation (10). The soil fertility index is a function of remaining soil mass, with the effect of soil erosion on soil fertility expressed through a logarithmic regression function adapted from the work of Sharpley (1985). Assuming the loss of particulate organic carbon represents a general loss in soil fertility, the relationship between soil loss and a soils remaining level of fertility is expressed through:

$$FI_t = FI_0 + \frac{ER_S}{100} \quad (1)$$

where FI_0 is the initial soil fertility index (FI_s), and ER_s is the Enrichment Ratio of either cumulative net sediment loss or soil formation up to the end of year *t*. The Enrichment Ratio is the ratio of the nutrient content of sediment (eroded or formed soil) to that of source soil, and is estimated using the data from Sharpley (1985) for the lost particulate organic carbon in relation to soil loss:

$$ER_f = \frac{1}{2\xi}\left[aSL_t + y_m - \{(aSL_t + y_m)^2 - 4a\xi y_m SL_t\}^{\frac{1}{2}}\right] \tag{2}$$

where SL_t is the negative cumulative change in soil mass to year *t* (tons/ha/year), the parameters ξ, α and y_m are derived through regression and have the values of 1.047e-7, 1.139 and 25.62 respectively (R^2 = 0.9947). In this equation, SL_t is a positive value to predict gains in soil nutrients during soil formation when the cumulative SFR_t is greater than cumulative soil loss.

Soil depth is expressed in the model through soil mass which accounts for user defined soil bulk densities, with a default value of soil bulk density calculated using the user defined proportion of Clay in the soil and the equation from Littleboy et al. (1999) if an actual value is not available. Change in soil mass is the difference between the rate of soil formation in each grazing area and the respective rates of soil erosion, such that:

$$\frac{dSmass}{dt} = SFR_t - SL_t \tag{3}$$

where SFR_t is the soil formation rate (tonnes/ha/yr) and SL_t is soil loss (tonnes/ha/yr) over year *t* (*t* = 365 days). Soil formation rate is based on the simple empirical relationship proposed by Wakatsuki and Rasyidin (1992) which utilises an approach of chemical weathering and mass balance accounting (Minasny et al., 2008). Soil formation rate, *SFR* (tonnes/ha/yr), is calculated as follows:

$$SFR = 0.1S\sum_{d=1}^{t}(Dr + Qr) \tag{4}$$

where *Dr* is the daily amount of soil water (mm/m^2/day) that drains beyond the rooting zone or the user prescribed erodible soil depth, *Qr* is the total amount of soil water (mm/m^2/day) that is runoff from the grassland, and *S* = 0.28 which is the constant for the unit amount of soils formed in grams as the result of the weathering of rocks (Wakatsuki and Rasyidin, 1992).

The combined loss of soil through wind and water erosion processes have been determined through a combination of empirical and process base models that utilise daily weather data. The total amount of soil loss, *SL* (tonnes/ha/year) is calculated as

$$SL = \sum_{d=1}^{t}(E_{Wd} + E_{Rd}) \tag{5}$$

where E_W is the amount of soil loss through wind erosion (t/ha/yr), E_R is the amount of soil loss through water erosion (t/ha/yr), summed over *d* days for each grazing area to derive a total annual soil loss (*t* = 365).

3.1.2 Wind erosion

The estimation of wind erosion is based on a combination of a process-based model to determine saltation, and an empirical model to determine the vertical flux of dust emissions into the atmosphere. The total horizontal sand flux, *Q*, the process of sand particles moving across the soil surface that dislodge dust particles, is calculated using the process based models of Shao et al. (1996) and Lu and Shao (2001), and applied as adapted by Kang et al. (2011). Due to the general lack of detailed particle size distributions, the total horizontal sand flux is based on the weighted sum of five discrete soil fractions, being very fine, fine, medium, coarse and very coarse sand, following the method described by Shao et al. (1996), and with proportions that can be modified by users. Table 1 presented here as a guide to particle size distributions.

Horizontal sand flux (*Q*) is calculated on an hourly time-step for each discrete sand particle size using diurnal hourly variations in air temperature and wind speed based on the functions defined by Thornley and France (2007). This includes the modification of the diurnal variation in wind speeds under different seasons (which can be modified by users) with summer being the highest (PD.WvarS = 2.0) and winter the lowest (PD.WvarW = 1.0) through the daily function:

$$W_{var} = \begin{cases} W_{Vm} + WV_d \cdot cos\left[2\pi \frac{(d-182.5)}{365}\right], \ Latitude > 0 \\ W_{Vm} - WV_d \cdot cos\left[2\pi \frac{(d-182.5)}{365}\right], \ Latitude \leq 0 \end{cases} \qquad (6)$$

where W_{Vm} is the mean annual diurnal variation in wind speed, and WV_d is half the difference in diurnal variation from the lowest to the highest diurnal variations in wind speed across the year (i.e. WV_d = (PD.WvarS-PD.WvarW)/2). The diurnal variation in temperature is also used to estimate diurnal variations in air density at a user defined elevation above sea level (m asl.) using the air density function of Van Donk et al. (2008).

The effect of soil moisture (volumetric soil moisture, *W*) on the threshold friction velocity ($u*_t$) is modified by the functions described by Fécan et al. (1999). This is driven by the Clay content of the soil which is set by users. The surface roughness factor, *R*, is calculated using the original function described in Shao (2001) and is based on the daily fractional ground cover in each grazing area. The parameter C_λ is used to calibrate the model for the quantity of dust emissions under different soil types, with a default value of $5e^{-5}$ used.

The vertical dust flux, F, is based on the function described by Lu and Shao (2001), due to adequately achieving a balance between complexity, parametrisation and applicability across a broad range of soils (Kang et al., 2011). Assumed values for $C\alpha$ (PD.Ca) and a soils plastic pressure, p (PD.p), are set at 1 and 125000 respectively, and can be modified by users. In this function, f, being the total volumetric fraction of dust in the soil is based on the definition of dust provided by Lu and Shao (2001). By using this relationship for settling velocity, and by solving against Stokes Law, the diameter (D_{ps} , µm) and proportion of the eroded soil particles, f, that can be lifted into suspension for extended periods, is calculated as such:

$$D_{ps} = 1e^6 \left[\frac{(0.7u^* \cdot 18\mu)}{g(\rho_p - \rho_a)}\right]^{1/2} \quad (7)$$

where $u*$ is the friction velocity of wind, μ is the viscosity of air (1.8e-5 N s m^{-2}), g is gravity (9.8 m s^{-2}), ρ_p is the particle density of soil (2600 kg m^{-3}), and ρ_a is the particle density of air (1.29 kg m^{-3}). The volumetric fraction of dust, f, is based on the proportion of soil particles equal to or less than D_{ps}, using a linear interpolant of the cumulative proportions of soil particle sizes, which is based on the user define soil particle size distributions.

Table 1: Guidelines to the proportion sand, clay and silt content, and sand particle size distributions under different soil types (USDA, 2011).

Tex. Name	Sand Tt (%)	Sand (percent fraction of Tt sand)					Silt (%)	Clay (%)
		V coarse	Coarse	Med	Fine	V fine		
Silty clay	7	1	2	2	1	1	48	45
Clay loam	33	6	6	7	7	7	34	33
Silty clay loam	11	2	2	2	2	3	56	33
Clay	18	3	3	4	4	4	17	65
Sandy clay	53	10	10	11	11	11	7	40
Loam	41	8	8	8	8	9	41	18
Silt loam	21	4	4	5	4	4	66	13
Sandy loam	65	11	11	11	16	16	24	11
Coarse sandy loam	63	15	30	6	6	6	27	10
Fine sandy loam	63	5	6	6	31	15	27	10
Sandy clay loam	63	11	11	11	15	15	27	10
Very fine sandy loam	63	2	3	3	18	37	27	10
Silt	7	1	1	2	2	1	88	5
Loamy fine sand	83	7	7	7	55	7	12	5
Loamy coarse sand	83	16	16	17	17	17	12	5
Fine sand	93	7	7	8	60	11	4	3
Loamy sand	83	10	10	10	23	30	12	5
Sand	93	20	20	20	15	18	4	3
Loamy very fine sand	83	5	5	5	8	60	12	5
Very fine sand	93	3	4	4	22	60	4	3

3.1.2.1 Calibration & validation

Du et al. (2018) indicated that grasslands across China over the period of 2001-2013 eroded at a rate of around 0.12-0.17t/ha/year. Shao (2004) compiled various data sets which indicates that a U* of around 0.4 adequately predicts the occurrence of dust emission events, at rates of around 100ug/m2/s ~ 0.0001g/m2/s. Zhang et al. (2018) indicates erosion rates of 0.2-2.5t/ha/yr in Inner Mongolian grasslands, or ~3t/ha/yr in 2006 and 24t/ha/yr being the grasslands mean. They also showed that the fractional vegetative cover during these dust emission events ranged around 22-28% (desert steppe), typical steppe 30-40%, sandy steppe (which is similar to desert steppe) at around 10-20%. These values were used to calibrate and validate the dust emissions model in the StageTHREE SGM.

3.1.3 Water erosion

The estimation of soil erosion due to rainfall runoff is modelled using the Revised Universal Soil Loss Equation as defined by Littleboy et al. (1999). Users can modify a number of key parameters in the model to more accurately reflect the erosivity of different soils, such as the curve number for average antecedent moisture conditions, maximum reduction in curve number at 100% cover, and the MUSLE soil erodibility factor.

3.2 Modelling grassland growth

There are a number of mechanistic grassland growth models available (Thornley and France, 2007) as well as single function models which account for net grassland production (Woodward, 1998). Previous studies and reviews have shown that simple models of grassland growth may adequately represent the changes in net grassland production (Behrendt et al., 2013a; Behrendt et al., 2013b; Cacho, 1993). These simpler models may be adequate for making management decisions when they provide dynamic descriptions of the key variables used in predicting changes in production (Woodward, 1998). An equation that relates grassland growth to grassland mass, LAI or height, coupled with descriptions of monthly changes in grassland quality (DMD) is all that is required in this model as the animal-plant-resource interactions are the main concern in the simulation model.

Using a modification of the growth index method proposed by Fitzpatrick and Nix (1975), the effects of daily temperature (air and soil), solar radiation, and soil moisture on plant growth controls and interacts with a sigmoidal grassland growth function (Cacho, 1993) in the SGM (Liu, 2017). In these sub-models, the growth of desirable and less-desirable species are modelled independently of the area being occupied, as the grazing area is assumed to be homogenous in micro-climate, soil type and fertility. At a grazing area (field) level, soil water balance and dynamics are modelled using the capacitance approach described by Johnson (2013), which also links to rate of soil formation through deep drainage and soil erosion through runoff. The proportional distribution of biomass to each of the digestibility pools is based on a modification of the equations described by Freer etal (2012), and the *StageTHREE* SGM models the DMD pool distribution for desirable and less-desirable species on a monthly time-step, although the aggregated biomass within pools are available to grazing livestock for consumption through selective grazing. In combination, this allows the effective representation of differences in both the productive capacity and quality (DMD) of desirable and less-desirable species to be more rigorously expressed in its influence on livestock production, especially as the state of the grassland resource changes in response to climate and management over the long-term.

3.2.1 Grassland sub-model details

In each grazing area grassland sward components, being the partial area under 'desirable' species and the partial area under 'less-desirable' species, are modelled separately on a daily time step (

Figure 3.1). To the grazing animal, the grazing area represents an even distribution of dry matter from the two species groups based on the relative partial areas of the grazing areas occupied by each species group.

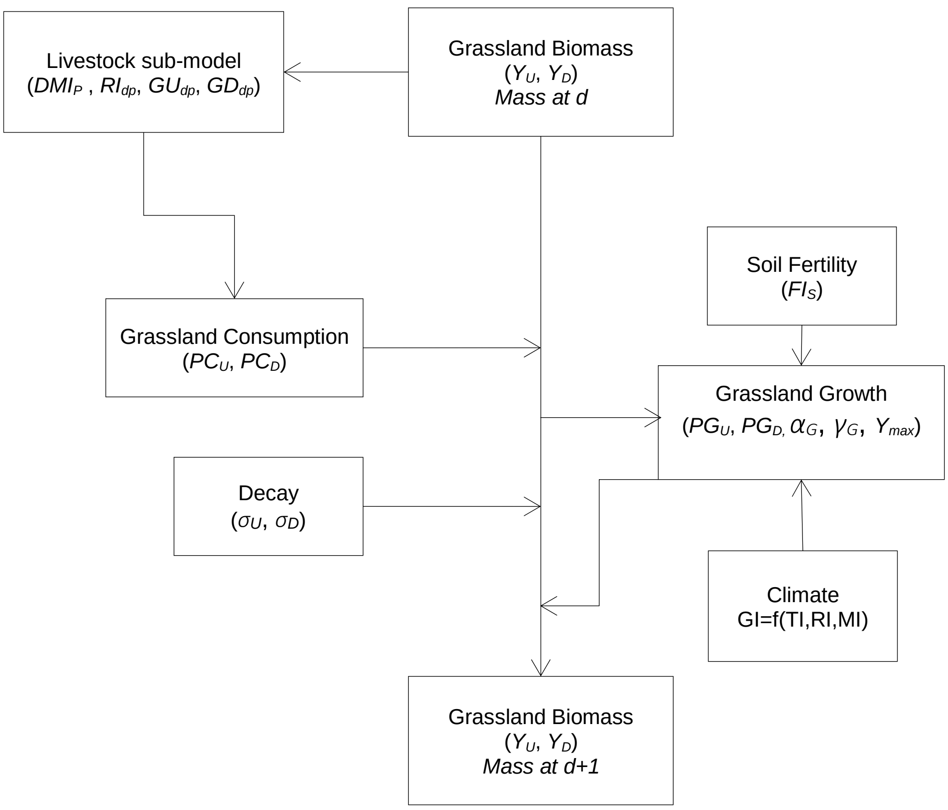

Figure 3.1: Diagrammatic outline of the grassland sub-model.

The changes in the partial area of the grazing area occupied by either the desirable or less-desirable species groups is adjusted annually in response to the type of year and the relative rate of biomass harvest (grazing management). This 'partial' paddock approach for modelling the areas of a grazing area under different species groups was adapted from Loewer (1998).

3.2.1.1 Grassland biomass

The daily change in available grassland dry matter, net of any supplements being fed, is a function of the grassland biomass consumed by grazing livestock and the growth of grassland from the remaining biomass. Grassland growth and consumption is modelled in each of the desirable and less-desirable sward components.

The process of grassland consumption and growth assumes that the grazing livestock harvest grassland biomass before its growth for that day is calculated. The change in grassland biomass for desirable (dY_D) and less-desirable (dY_U) species at the end of each day is calculated as follows.

$$dY_D = PG_D - PC_D - Y_D.\max(GI_d.\sigma_D, 0.4\sigma_D) \quad \text{and}$$
$$dY_U = PG_U - PC_U - Y_U.\max(GI_d.\sigma_U, 0.4\sigma_U) \tag{8}$$

where PG_D and PG_U are the quantities of grassland biomass grown per day (kg DM/ha/d) after grazing by livestock, PC_D and PC_U are the quantities of grassland consumed by the grazing livestock (kg DM/ha/d), and σ_D and σ_U are the maximum daily decay rates of grassland due to microbial breakdown, trampling and defecation by grazing livestock. The daily decay rate varies throughout the year in response to the grassland growth index (i.e. $GI_d.\sigma_D$, $GI_d.\sigma_U$) with a minimum daily decay rate of 40% of the user prescribed maximum rate of daily decay (i.e. $0.4\sigma_D$, $0.4\sigma_U$) based on Cacho et al. (1995).

The residual grassland biomass, *Y*, in kg DM/ha for day *d* is the residual amount of grassland biomass after grazing, decay and growth has been accounted for.

$$Y_d = Y_{d-1} + dY \tag{9}$$

3.2.1.2 Grassland growth

Grassland growth is based on an approach that combines the sigmoidal pasture growth curve of Cacho (1993) and the growth index models developed by Fitzpatrick and Nix (1975) and Nix (1981). The key parameters of the sigmoidal growth curve are estimated using field data. For notational convenience, the *U* and *D* subscripts are not included in the following equations which have been applied separately to each grassland functional/species group.

The individual growth of grassland biomass (kg DM/ha/d) for desirable and less-desirable species is calculated as follows:

$$PG = \alpha_G \frac{Y^2}{Y_{max}} \left[\frac{Y_{max}-Y}{Y}\right]^{\gamma_G} FI_S \cdot GI_d \cdot SI_d \qquad (10)$$

where α_G is a growth parameter influenced by the annually modified soil fertility effect (FI_S) and the daily growth index (GI_d) and seasonality index (SI_d), Y_{max} is the maximum sustainable herbage mass or ceiling yield when an equilibrium is reached between new growth and the senescence of old leaves (but excluding the decay of plant material), and γ_G is a dimensionless parameter with a value in the range of $1< \gamma_G <2$ (Cacho, 1993). The parameter α_G is varied by stochastic multipliers (SM_t, equation 19, page 20) which are based on the ratio of total annual rainfall to long-term average rainfall, i.e. in high rainfall years the α_G increases, and vice versa. This was found to best match typical summer rainfall dominant continental climates found across Chinese and Mongolian grasslands.

Figure 3.2 illustrates the relationship between grassland biomass and grassland growth through a sigmoidal growth curve. It indicates maximum net grassland growth rate, G^{max}, occurs at grassland mass Y^*. Cacho (1993) showed that the value of α_G effects the height of the growth curve, G^{max}. The parameter γ_G interacts to affect the position of Y^* along Y and the height of the growth curve. The parameter Y_{max} interacts to determine the height of the growth curve and, to a lesser extent, the position Y^* along Y.

Values of these parameters are derived individually for the desirable and less-desirable sward components.

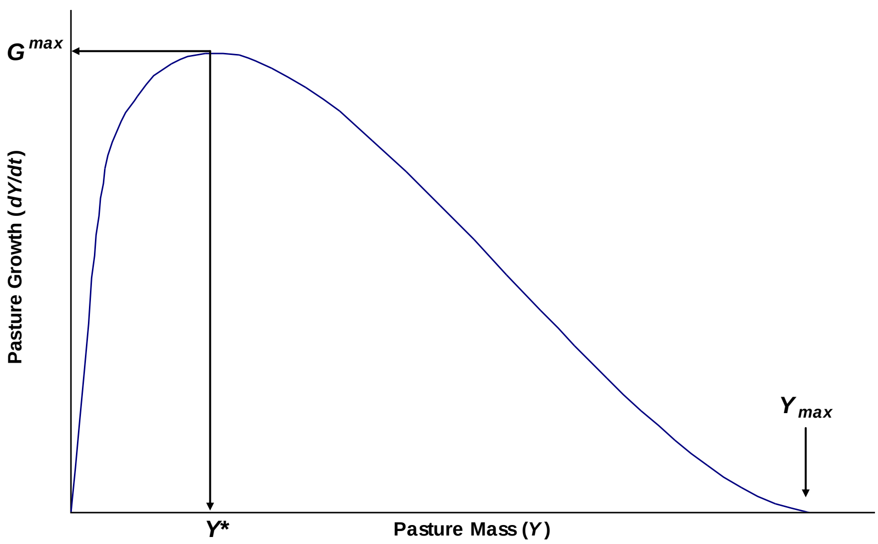

Figure 3.2: Sigmoid grassland growth curve adapted from Cacho (1993).

The daily growth index, GI_d, is derived using a method adapted from Fitzpatrick and Nix (1975) and Nix (1981). The method combines the potential effects of soil and ambient air temperature, solar radiation and soil moisture on limiting daily grassland growth, such that:

$$GI_d = min(LI_d, TI_d, MI_d) \quad (11)$$

where LI_d is the light or solar radiation index, TI_d is the temperature index, and MI_d is the soil moisture index. The light index, LI_d , is based on the relationship described by Nix (1981):

$$LI_d = 1 - e^{-3.5R} \quad (12)$$

where R is the ratio of total daily solar radiation (in cal's) to 750 cal cm^{-2} d^{-1} as follows:

$$R = \frac{750Rn}{41840} \quad (13)$$

where Rn (J m^{-2} d^{-1}) is the daily net radiation during the daylight period and has been derived from the equations described by Johnson (2013) that take into account the effects of daily temperature, daylight hours, latitude, and relative humidity.

The temperature index, TI_d, combines the effects of ambient air temperature and soil temperature to constrain plant growth at times when soil temperature is too low to support plants and roots to grow, or below ground biochemical process are inactive or limited, such that:

$$TI_d = \begin{cases} TI_a \, , \; T_s > ST_T \\ 0 \, , \; T_s \leq ST_T \end{cases} \quad (14)$$

where TI_a is temperature index based on air temperature, T_S is soil temperature at 10cm depth (°C), and ST_T is the user defined soil temperature threshold (°C). Soil temperature at 10cm depth is modelled using the functions described by Zheng et al. (1993) which allow for the effects of both vegetation and snow pack depth on changes in soil temperature with changes in air temperature. The temperature (or Thermal) index, TI_a, is based on the relationship defined by Nix (1981) which allows users to define lower and upper temperature thresholds for a species, as well as the optimum daily temperature for growth, at which the index is at unity. The value of b, that governs the inflexion of the curves, is assumed to take a value of b = 2, which represents most microtherm, mesotherm and C_4 megatherm species (Nix, 1981). This fixed value can be modified through the model's base parameters.

The moisture index, MI_d, represents a daily soil moisture balance sub-model that considers transpiration from the vegetative canopy, evaporation of any surface water, movement of water out of the root zone, the potential runoff of water during rainfall events, and the evaporation of water directly from the soil. The moisture index is based on the method described by Johnson (2013) that produces an index that represents the limiting effect of soil water content on transpiration. This index is at unity at potential transpiration when there is no limit in available soil moisture, and declines from the recharge point to zero under wilting point conditions. When soil moisture in excess (> field capacity) it declines to a point of saturated water content. The index value at saturated water content is a fixed value of W_L = 0.3 and can be modified through the model's base parameters.

The daily change in available soil water, δ_{ASW} (mm/day), and is calculated as follows:

$$\delta_{ASW} = P - (E_t + Q + E_S + D) \tag{15}$$

where P is the amount of precipitation into the soil allowing for rainfall and melting snowpack (snow dynamics are based on the functions of Zheng et al. (1993)), E_t is the potential transpiration (based on the functions of Johnson (2013)) when temperature and light do not completely limit growth (when TI_d & LI_d = 0), Q is the amount of runoff (mm/day) occurring during any rainfall or snow pack melt event as defined by Littleboy et al. (1999), E_S is the evaporation from the soil as defined by Johnson (2013), and D is the daily drainage of water out of the root zone as defined by Littleboy et al. (1999).

The seasonality index, SI_d, allows for accelerated grassland growth rates, primarily leaf extension rates, due to physiological changes in grasses during spring (Wingler, 2015; Wingler and Hennessy, 2016). The period of accelerated growth is assumed to occur due to increasing day length and starts from the spring equinox[6] and continues until the longest day of the year, the summer solstice[7], which is taken to be the end of spring (Smith and Stephens, 1976). The seasonality index is defined as follows:

$$SI_d = \begin{cases} 1 + \left(1 - \frac{2{s_d}^{\beta_{si}}}{2}\right) \cdot \varepsilon_s \cdot \left(1 - P_{Leg}\right), & s_d > 0 \; and \; s_d < 0.5 \\ 1 + \left(0.5 \cdot (2 - 2s_d)^{\beta_{si}}\right) \cdot \varepsilon_s \cdot \left(1 - P_{Leg}\right), & s_d \geq 0.5 \; and \; s_d \leq 1 \\ 0, & s_d = 0 \end{cases} \tag{16}$$

where s_d is the spring day ratio, β_{si} is the factor that governs the inflexion of the curves and is assumed to take a value of β_{si} = 4, ε_s is the seasonality effect which takes a value of 0.625 for C3 species and 0.1 for C4 species based on the data of Parsons and Robson (1980) and Smith and

[6] Spring equinox is defined as either the northward (DOY 78) or southward equinox (DOY 263) depending on the hemisphere the modelled system is in by the user defined latitude
[7] Summer solstice is defined as either DOY 171 in the northern hemisphere or DOY 355 in the southern hemisphere.

Stephens (1976), and P_{Leg} that represents the user defined proportion of legumes in the grassland. The spring day ratio, s_d, is determined as follows:

$$s_d = \begin{cases} max\left(0, \frac{S_{mDOY} - d}{S_{mDOY} - S_{sDOY}}\right), & d < S_{mDOY} \\ max\left(0, \frac{d - S_{mDOY}}{S_{eDOY} - S_{mDOY}}\right), & d \geq S_{mDOY} \end{cases} \quad (17)$$

where d is the Day of Year (DOY), S_{mDOY} is the DOY when maximum spring growth occurs, S_{sDOY} is the DOY that accelerated spring growth starts (spring equinox), and S_{eDOY} is the DOY when accelerated spring growth ceases representing the end of spring and growth switching from vegetative to reproductive (summer solstice).

3.3 Modelling botanical composition of the grassland resource

Changes in plant composition are often the first signs of degradation. In mechanistic grassland or crop models, plant composition is generally modelled on the assumption of competitive interference for resources such as water, light and occasionally nutrients. The limitation of this method applied to grassland resource management is that it does not cope well with simulating more than two competing species. Furthermore, there is the underlying assumption in some models that species persist indefinitely and homogenously occupy space within the sward. Rather than modelling explicitly how plants interact, the response of plants to changes in their environment can be represented by the net ability of a group of plants to capture resources and compete (Kemp and King, 2001). For decision making, the modelled changes in botanical composition need to respond over the long term and represent the changes in the basal area of competing species, especially in response to sporadic events such as droughts (Jones et al., 1995).

The empirical grassland composition sub model within the *StageTHREE* SGM developed by Behrendt (2008) adapts the method proposed by Loewer (1998) on the use of 'partial' paddocks. In Loewer's GRAZE model it is assumed that each species is uniformly distributed throughout a paddock and that the initial area they occupy remains fixed. However, the dry matter availability of each species is varied through selective grazing (driven by differences in forage quality) and independent species growth, with the regrowth of these species then dependent upon the residual biomass at any one time. In the *StageTHREE* SGM the space occupied by species is assumed to be variable and respond to climate, management, inputs and the state of soil resources. This enables the cycle of grassland degradation to very low populations of desirable species to be modelled adequately. It also enables the potentially positive response of the grassland resource condition to tactical grazing management, production system modification, supplementary feeding and/or fertiliser inputs to be modelled (Behrendt, 2008; Behrendt et al., 2013a, 2016).

This empirical modelling approach is analogous with in-field measures of basal areas of grassland species and is also similar to the methods of basal area adjustments applied in some rangeland models (Stafford Smith et al., 1995). Separation of grassland yield and basal area of different species groups is also justified as basal area provides a more meaningful and stable indicator of ecological or botanical composition change than grassland yield (Cook et al., 1978b).

The population of desirable species in the sward is modelled by using differential equations describing population growth and the impact of harvesting (determined by the consumption rate of the desirable component of the grassland). The value of the livestock impact parameter reflects the sensitivity of botanical composition change to consumption rate on species phenology. These represent the grassland resource as an exploitable renewable resource as described by Clark (1990). In the grassland composition sub-model a logistic growth model is used for regeneration of desirable species with the rate of change influenced by both a soil fertility factor (which is influenced by inputs such as fertilizer and soil erosion) and annual rainfall factor through the use of stochastic multipliers (Cacho et al., 1999). This empirical method adapts the concepts of state and transition models of rangelands (Westoby et al., 1989), with the benefit of an indefinite number of grassland states and responses to climate, management and input factors. The modified partial paddock approach developed also allows the desirable components within the sward to increase their basal area over time. The spatial measure of grassland composition in the model is similar to basal measurements common in agronomic experiments (Whalley and Hardy, 2000).

In the model developed by Behrendt (2008), two grassland populations are defined. They represent desirable and less-desirable species groups. The two groups may have different growth parameters, different responses to improvements in soil fertility and different dry matter digestibilities. All of these factors combine to influence the potential carrying capacity and livestock production from the system. This process also allows the expression of changes in the quality of the grassland resource in response to changes in grassland composition and the total amount of herbage available to grazing livestock.

3.3.1 Grassland dynamics sub-model details

The total area of grassland is comprised of two components, Desirable species and Less-desirable species so that $X_D + X_U = 1.0$, where X_D is the proportion of desirable species and X_U is the proportion of less-desirable species within the grassland sward (Figure 3.3). This is a spatial measure of sward composition similar to basal measurement common in agronomic experiments (Whalley and Hardy, 2000). The growth of the sward is independent of area being occupied, as the paddock area is assumed to be homogenous in micro-climate, soil type and fertility.

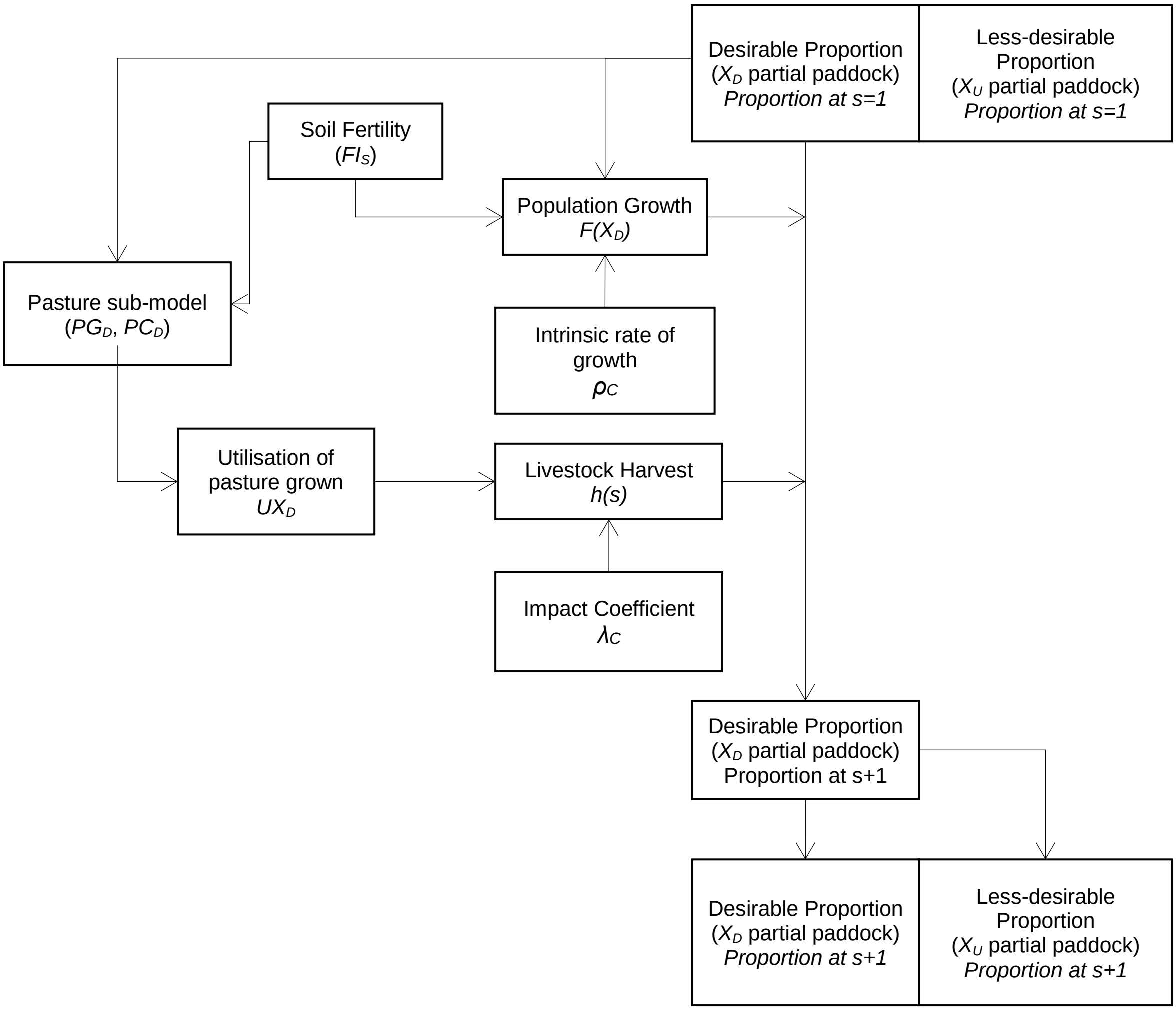

Figure 3.3: Diagrammatic outline of grassland composition sub-model. Adapted from Behrendt (2008).

Annual changes in the potential growth of the sward components are accommodated for by adjusting parameters on an annual basis. To model the impact of stochastic climate conditions, these parameters are adjusted using stochastic multipliers as described by Cacho *et al.* (1999).

Annual changes in the botanical composition of the sward are assumed to be driven by the effect of management and climate on the desirable components within the sward, as this group is assumed to have a higher potential growth rate and a higher digestibility and hence is more likely to be consumed than the less-desirable species group. A further assumption is that the less-desirable species group tends to be invasive and opportunistic wherever there is a decline in the area of the desirable species group. It is also assumed that if more desirable species are given the opportunity through adequate soil fertility, tactical grazing rests or reduced grazing pressure during favourable seasons, they will expand their basal cover and move eventually towards attaining dominance of the sward.

The method applied in this study to model grassland resource composition as a renewable resource is similar to that often applied to exploited biological resources (Clark, 1990). These models are based on differential equations. In this application to the renewable resource of desirable species, the equations are in the form:

$$\frac{dX_D}{ds} = F(X_D) - h(s) \qquad (18)$$

where $X_D = X_D(s)$ denotes the proportional area occupied by desirable species within a sward, $F(X_D)$ represents the rate of growth in the area of desirable species, and $h(s)$ is the impact of harvest or grazing on the area occupied by desirable species in a growing season.

3.3.1.1 Desirable species population growth

The growth in the population of desirable species, measured as the change in the area of the paddock they occupy, is represented by a function describing their rate of growth in the absence of any harvesting or grazing. The rate of growth in the basal area of desirable species under limited spatial and environmental resources is described using a logistic growth model:

$$F(X_D) = \rho_C SM_t X_D \left(1 - \frac{X_D}{\mathrm{K}_C FI}\right) FI \qquad (19)$$

where ρ_C is the intrinsic rate of growth in the area occupied by desirables species, and κ_C is the environmental carrying capacity, or the maximum proportion of the grasslands area that the desirable species may occupy within a sward. The rate of growth of the desirable component of the grassland is also influenced by climate and soil fertility. The effects of climate variability are expressed through stochastic multipliers, SM_t, which is a ratio of the rainfall received in year t to the long-term average annual rainfall (or average for the rainfall data uploaded). The soil fertility effect, FI , potentially limits both the rate of growth in the population and the potential size of the population (Cook et al., 1978a; Dowling et al., 1996; Hill et al., 2005). Assuming the loss of particulate organic carbon represents a general loss in soil fertility, FI represents the index (subject to ≥ 0.01) of soil fertility in year t to that of initial soil fertility.

The parameter ρ_C is subject to $\rho_C > 0$ and $\rho_C < 1.0$, and is variable as it relates to climate and growing season characteristics. This parameter is varied through the stochastic multipliers depending on the type of year in which the shift in botanical composition is being modelled. Figure 3.4 illustrates the impact of different ρ_C values on $F(X_D)$ (post multiplication by SM_t). Higher ρ_C values are expected in favourable years where climatic conditions favour vegetative growth and reproduction of desirable species and lower ρ_C values are expected under poorer climatic conditions (e.g. drought).

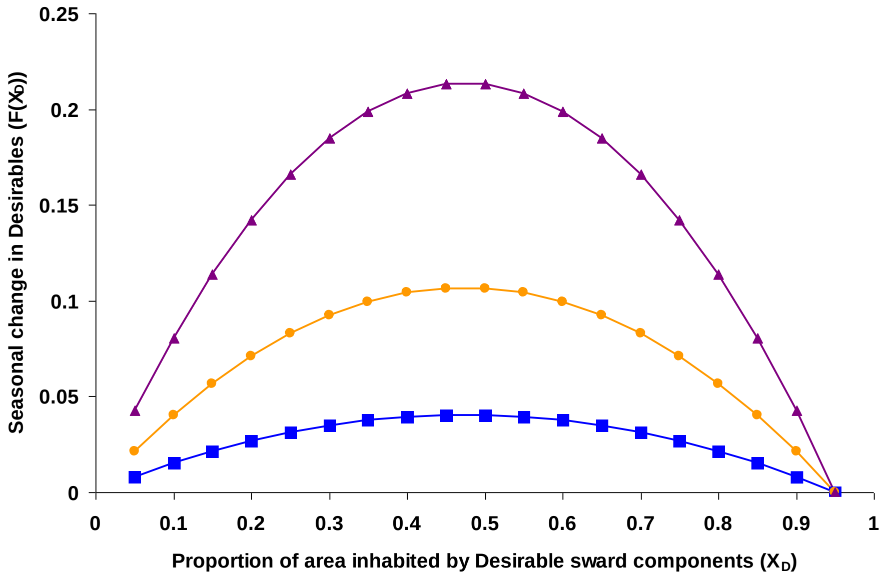

Figure 3.4: Influence of ρ_C and area occupied by desirable species on their rate of expansion in a season; ρ_C = 0.9 (▲),ρ_C = 0.45 (●),ρ_C = 0.17 (■), κ = 0.95 and *FE* = 1.0. (Behrendt, 2008)

3.3.1.2 Impact of grazing livestock on desirable population

The effect of any livestock grazing on sward structure, $h(s)$, is estimated using the predicted utilisation by grazing livestock of the grassland grown in a season. This considers both of the components that make up grazing pressure on the sward, namely stocking rate and grazing time, and the stochastic growth of the grassland in a growing season.

$$h(s) = UX_D \lambda_{SC} \tag{20}$$

where UX_D is the utilisation of the desirable species growth in a year by grazing livestock, and λ_{SC} is the impact coefficient of grazing livestock on the population of desirable species components within the sward. The measure UX_D is similar in principle to the measure of grazing pressure defined by Doyle *et al.*(1994) and represents the consumption rate of grown pasture. The parameter λ_{SC} is positive. The value of the parameter reflects the sensitivity of botanical composition change to grazing pressure on species phenology.

Figure 3.5 shows that under a constant level of λ_{SC} and with poor seasonal conditions, such as droughts, which induce low intrinsic rates of growth in the population of desirable species (ρ_C=0.17), moderate levels of harvest by grazing livestock (UX_D=0.45) leads to a negative impact

($h(s)>F(X_D)$) on the size of the desirable population. As seasonal conditions improve (ρ_C =0.45 and 0.9) there are states in which moderate harvest levels by grazing livestock allow the proportion of desirable species within the sward to increase (in states when $h(s)<F(X_D)$).

This method encapsulates the effect of different grazing pressures in different seasons on changes in botanical composition. The default value for λ_{SC} was estimated statistically from the simulation of in-field experimental data and guided by expert opinion.

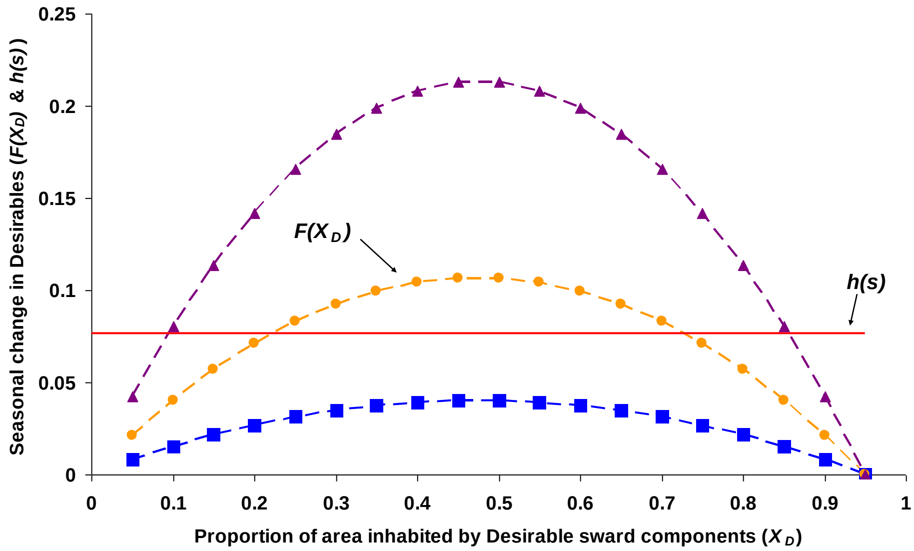

Figure 3.5: Livestock harvesting impact $h(s)$ (—) and predicted rates of expansion by desirable species within the sward; ρ_C = 0.9 (▲),ρ_C = 0.45 (●),ρ_C = 0.17 (■), κ = 0.95, FE = 1.0; when UX_D = 0.45 and λ_{SC} = 0.17. (Behrendt, 2008)

Typically the harvesting effect is based on the concept of *catch-per-unit-effort* where the harvest is linearly proportional to the size of the population (Clark, 1990). This has been modified in this application of the model due to the way grassland utilisation by grazing livestock is estimated.

$$UX_D = \max\left(\mu_C , \frac{\sum_{d=1}^{D} PC_{Dd}}{\sum_{d=1}^{D} PG_{Dd}} \right) \tag{21}$$

where μ_C is the maximum utilisation constraint on the impact of grazing livestock on the population of desirables species, PC_D is the quantity of dry matter consumed from only the desirable components of the sward (kg DM/ha), and PG_D is the quantity of dry matter grown from the desirable components of the sward (kg DM/ha). As utilisation over a year is calculated based on the consumption and growth of individuals in the population of desirable species, the need to make *h(s)* a function of X_D is removed. Thus *h(s)* remains constant across all states of botanical composition.

3.4 Modelling livestock performance

To adequately represent the production of wool and meat, the livestock sub-models needed to be capable of responding to changes in the available grassland mass and changes in botanical composition with its inherent effect on feed quality. A more mechanistic approach was taken in developing the livestock sub-models. The livestock sub-models are based on many of the equations described by the modified Technical Paper Freer et al. (2012) and Freer *et al.* (2007), both of which superseded the preceding publication, Freer *et al.* (1997). These publications represent a revised version of the original report by SCA (1990) and fundamentally describes the functions used in the *GrazPlan* suite of decision support tools (Donnelly et al., 1997; Freer et al., 1997; Moore et al., 1997), which have been broadly applied and shown to adequately predict ruminant livestock performance under diverse environments. This was required to ensure there were adequate feedback mechanisms between the selective grazing by livestock and changes in botanical composition, grassland quantity and growth. The framework has been developed for the modelling of sheep, goat, cattle and Yak production systems.

For each livestock species, three types of animals are modelled, being females, males for breeding, and castrated or non-castrated males not used for breeding that are the progeny of the females. For breeding females and non-breeding males an unlimited number of age cohorts can be modelled with differing selling and supplementary feeding policies applicable across different age cohorts. In these sub-models, grazing livestock are capable of selectively grazing between the digestibility pools of total combined dry matter available to them from each partial area. This selective grazing assumes that grazing ruminants will aim to maximise their intake based on the dry matter digestibility of plants. To estimate the actual dry matter intake of grazing livestock and the digestibility of their diets from the dry matter available in each digestibility pool, the model assumes that the animal attempts to consume its potential intake from each pool from the highest to lowest digestibility in succession. The ability of animals to select from each pool is related to the quantity of dry matter in each pool and its digestibility. The more an animal satisfies its potential intake from a higher digestibility pool, the less will be consumed from the lower digestibility pools. The substitutional effect of feeding supplements on grassland dry matter intake, as well as its impact on diet digestibility and energy consumption for livestock maintenance and production, is accounted for. The grassland consumption from the desirable and less-desirable components are assumed to be evenly distributed throughout the grazing area depending on the weighted consumption from the digestibility pools and the proportion of the grazing area occupied by desirable and less-desirable species groups. Such models, that base diet selection between species or species groups on the digestibility of the dry matter, have been validated by research into the influence of grassland degradation on diet selection and livestock production (Chen et al., 2002).

The issue of flock structure has been accounted for through the modelling of flock and herd structures and dynamics using a daily state flow model with an unlimited number of age cohorts available (although the model is currently limited to 15 age cohorts, this can be extended). On the birth DOY, all animals across all age cohorts move into the next age cohort. Concurrently, all variables relating to age (in days), bodyweights, fleece/hair weights, reproductive rates, and foetus weights are carried into the next age cohort. Each age cohort is modelled as a single representative animal, with the number in each cohort determined by reproductive and mortality rates, purchasing and selling policies.

One of the most significant direct externalities from grazing ruminant livestock are from the production of greenhouse gases, particularly methane. To determine the capacity of system management and use of grassland resources to reduce the emission intensity of methane (CH_4) and nitrous oxide (N_2O) outputs from ruminant livestock production (i.e. the units of methane per unit of animal product), IPCC Tier 2 functions (De Klein et al., 2006; Dong et al., 2006) have been adapted in the *StageTHREE* SGM. These functions predict the amount of methane produced and emission intensity for meat production from rumination (enteric CH_4), manure (CH_4) and nitrous oxide (N_2O) emissions from manure management (pasture & dry lot) for the whole flock/herd and convert them to 100-year Global Warming Potential (GWP_{100} AR5 values) carbon dioxide equivalents (kg CO_2e) (IPCC, 2014).

3.4.1.1 Supplementary Feeding

Supplementary feeding is also available as a means of substituting for the consumption of grassland dry matter or supporting the maintenance of livestock condition. Supplements are made available subject to supplementary feeding rules that relate to triggers and that are applied between specified days of the year across each age cohort and type. The supplementary feeding rules follow these steps while animals are grazing (not full time in warm shed/pen):

- Is the DOY between the specified *DOY Start Feeding* and the *DOY Stop Feeding* (***Grazing Area Input*** tab)? If true, then concurrently apply these two modifiable rules:

- Offer supplements if the total biomass available to grazing animals is less than or equal to the *Minimum Biomass (as kg DM/ha) to initiate feeding* on the ***Grazing Area Input*** tab.
- Offer supplements if the relative condition score of an age and class cohort is less than or equal to the *Supp. Feeding Rel. Cond.* threshold specified for each age cohort and class of animal (females, male progeny, breeding males) on the ***Livestock Input*** tab.

Relative Condition Score ranges from 0-1, with a value of 1.0 being at an animals Standard Reference Weight (SRW, kg liveweight) or a body condition score (BCS) of 3.0, and 1 BCS approximately equates to 0.15 in terms of Relative Condition (e.g. Rel.Cond. 0.85 ~ BCS of 2.0; Rel.Cond. 0.70 ~ BCS of 1.0). In terms of empty body weight (net of conceptus), 1 BCS unit equates to around 0.15 x SRW of liveweight, e.g. for sheep with a 60kg SRW, 1 BCS ~ 9kg Lwt. See Freer et al. (2007), pp 53-60, for detailed discussion of body condition scores for sheep, goats and cattle, and their interaction with production.

The quantity of supplement offered daily to each cohort of animal, S_a (kg DM/hd/day), is adjusted according to their Normal Weight which considers their age and previous weight gain. Such that:

$$S_a = NW_a \left(\frac{R_{SRW} \cdot S_{DM}}{SRW}\right) \qquad (22)$$

where NW_a is the normal weight of each animal cohort (by age and class) as defined by Freer et al. (2012) in equation 1a, R_{SRW} is the amount of ration offered (kg wet/head/day) assuming feeding adult animals at their SRW, and S_{DM} is the Dry Matter: Wet weight ratio for the supplements being offered.

3.4.1.2 Flock Structure

The size of the flock/herd is self-correcting to a user prescribed target level of females. At the DOY that surplus females are to be sold, the sale of adult females (>12 months of age) is adjusted across age cohorts to ensure the target number is maintained. The 'minimum proportion sold' from each age cohort is specified by the user on the ***Livestock Input*** tab under the parameter 'Selling Prop.'. If surplus animals exist, then the proportions sold increase in each age cohort at the same ratios across the age cohorts as specified under 'Selling Prop.' up to a maximum of 1.0 (100% of an age cohort sold). For adult male progeny (>12 months of age) they are sold as specified by the selling proportions indicated by the user. Breeding male (sires) selling and culling is automatically calculated to maintain the required number of sires (i.e. rams/bucks/bulls) required for joining. For both females and breeding males, the retained number (or 'purchased' for the case of males) of animals also allows for half of the expected annual mortalities as determined by the base mortality rate.

The model includes the option of specifying on the ***Livestock Input*** tab a Target Sale Weight for young animals (applied to animals <12 months of age only). If this option is selected, young animals, both females and young males breed from the females (i.e. male progeny), are sold at the specified selling proportions when they reach the Target Sale Weight or the defined DOY Sold, which ever event occurs first during their lifetime. The user should ensure that weaning occurs prior to the expected DOY Sold (whether this sale date is based on the defined DOY Sold or Target Sale Weight).

Daily mortality rates in the model are calculated using a modified approach to those described by Pepper et al. (1999) and Cacho et al. (1995). This function works on defining a empty body critical weight limit, EBW_{crit}, for each of the livestock class and age cohorts in the model (i.e. adult females, adult males, young animals), with daily mortality rate, MR_t , calculated as:

$$MR_t = CD_1 + \frac{max\left(0{,}1 - \frac{W_i}{EBW_{crit}}\right)}{365} \quad (23)$$

where CD_1 is the basal daily mortality rate for the flock or herd specified by the user, W_i is the initial base weight excluding the weight of a conceptus (kg), and EBW_{crit} is the critical weight limit (kgs Lwt), which is derived from:

$$EBW_{crit} = NW_a\big(1 - C_r(1 + RS)\big) \quad (24)$$

where NW_a is the normal body weight (kg Lwt) for each class and age cohort on any day, C_r is the critical relative condition constant that is adjustable within the model (PL.Cr with a default value of 0.26, although this can be adjusted for females, male progeny and breeding males), and *RS* is the relative size of each class and age cohort on any day (Freer et al., 2012). Within the daily state flow flock/herd model the process assumes that young animals (e.g lambs) do not die when breeding females (e.g. ewes) die, which corresponds to typical herder practice. These functions were found best to match sheep sector mortality data in Mongolia when climate and animal performance interactions were modelled on a daily time-step (*publication forthcoming*). The model also includes an assumed automatic weight gain with mortalities in the flock/herd. i.e. it is assumed that the lightest animals are at the highest risk of dying, as such, with mortality comes an incremental increase in the mean base weight of surviving animals within the system, as described by Freer et al. (1997).

Reproductive rate (including both the proportion of singles, twins and triplets conceivable) is calculated daily for each age cohort and stored, as well as relative size and relative condition of the breeding females. This matrix is drawn upon at the time of conception to derive the reproductive rate for inclusion in both the flock/herd structure calculations and in calculating ME balances for conceptus growth and lactation, as well as conceptus and lactation factors that contribute to determining I_{max} (Relative Grass Intake) (Freer et al., 1997; Freer et al., 2012).

3.4.2 Grazing Management

There are two basic choices available on the ***Grazing Area Input*** tab for designing the grazing management of livestock on the grassland. These are either structured around a time-based grazing system or a biomass based grazing system. The time-based gazing system is ideal for simulating different seasonal grazing areas (e.g. summer, autumn, winter, spring), as multiple grazing areas can be specified with a range of short or long grazing periods. The biomass-based system is ideal for testing the effect of placing sustainability or optimal management constraints on a grazing system. In this instance, there are two measurable and identifiable biomass levels used to trigger either livestock movements between grazing areas or complete destocking of grasslands. For both grazing systems, up to 30 grazing areas can be specified[8].

Figure 3.6 shows the pathways for setting the model to run different available combinations of grazing management and the use of warm-sheds/pens. There exists the option to use the warm shed/pen according to DOY, insufficient biomass and/or just overnight.

[8] The number of grazing areas can be expanded upon request, although this comes with obvious increases in the execution time and storage requirements for data outputs.

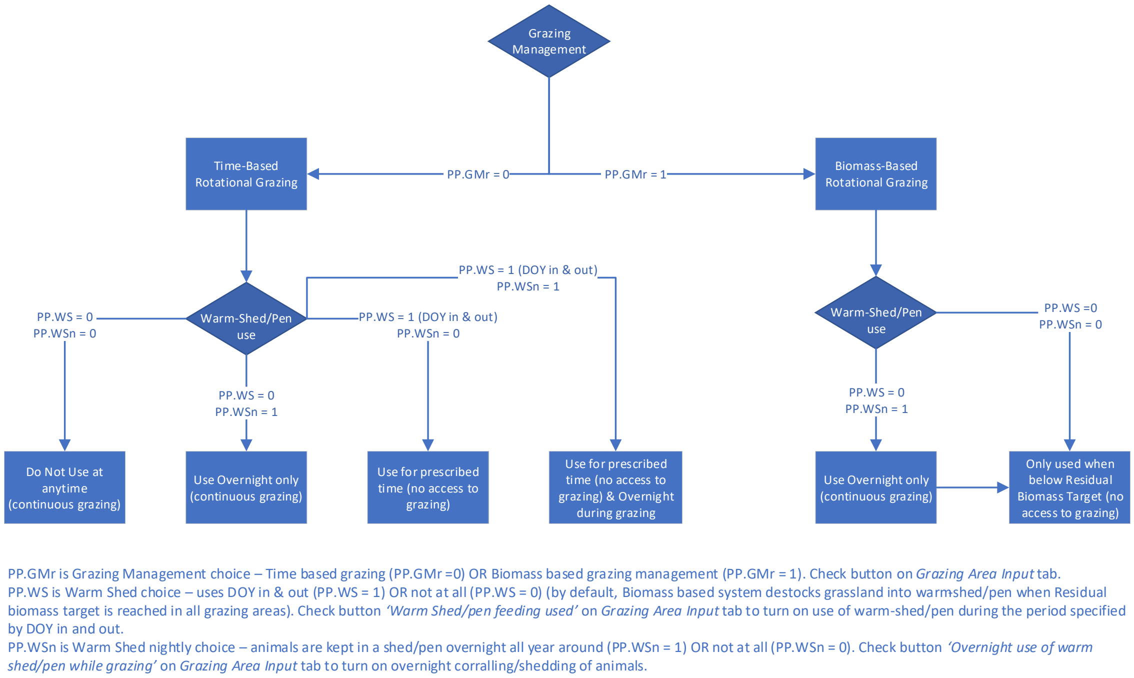

Figure 3.6: Flowchart for setting up different combinations of grazing management and the use of a warm-shed/pen.

Care should be taken in setting the characteristics of the warm-sheds/pens available. The work of Zhang et al. (2016) indicates that warm sheds that are built to greenhouse standards with glass, heating and minimal air gaps are capable of maintaining inside temperatures of around -5 to 5°C during winter days when external temperatures are -15 to -25°C. Additionally, wind speed maybe reduced by over 80%, and depending on the design, may protect animals from any rainfall or snow. Typical warm sheds, however, tend to only maintain inside temperatures 10-11°C higher than outside temperatures (Kemp and Michalk, 2011). An example of how continuous shedding/penning or overnight shedding/penning influences daily variations in livestock temperature exposure is shown in Figure 3.7.

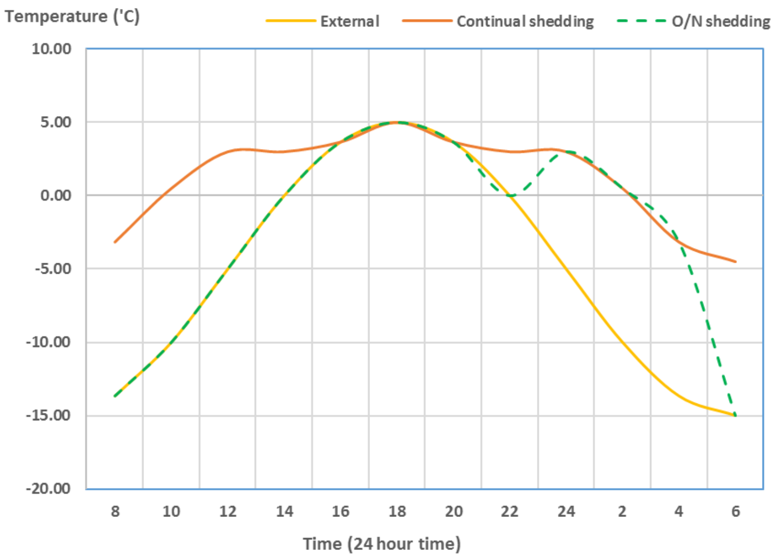

Figure 3.7: Influence of warm shed/pen on livestock temperature exposure under continuous and overnight shedding only. Assumes a minimum warm shed heating capacity of 10.5°C.

For a time-based grazing system:

1. The user selects 'Time (Day) based grazing' on the ***Grazing Area Input*** tab.
2. The user then needs to define the number of days, Grazing Days (max) that the animals spend in each grazing area. Grazing areas need to be in sequential order from DOY1 (1st January).
3. If the 'Warm Shed/Pen Feeding used' option is not selected, then the model assumes the animals are continuously grazed around all grazing areas for up to the specified maximum number of grazing days for each grazing area. The model will always follow the sequence of grazing areas specified in the table from the first (top) grazing area listed and downwards.
4. If the 'Warm Shed/Pen Feeding used' option is selected, the user will need to specify the 'DOY into Warm Sheds/pens' and 'DOY turned out from Warm Sheds/pens'.[9]
5. The user can specify the quality of the warm shed/pen given its expected capacity for maintaining higher temperatures (*PP.WSTmin* – minimum heating capacity of air inside the warm shed/pen, which by default is limited to a maximum inside temperature of 3°C while heating, as the work of Zhang et al. (2016) indicated no further gains from

[9] If animals are destocked from grasslands into warm shed/pen, energy for moving is equal to zero.

heating occurred beyond this), reducing the wind speed experienced by animals and whether or not animals are exposed to rainfall or snow.

6. While animals reside within the warm shed/pen, they are assumed to be fed the specified supplementary feed available to the herder[10]. When animals are grazing, the offering of supplements follows the specified supplementary feeding rules.

For the biomass-based grazing system:

1. The user selects 'Biomass (DM/ha) based grazing' on the ***Grazing Area Input*** tab.
2. The user then needs to define the Grazing Residual Target (Kg DM/ha – *a minimum biomass target that would be used for the optimal management of growing grasslands*) and the Critical Residual Biomass (Kg DM/ha – *a minimum biomass target that would be imposed for maintaining the sustainability of a grassland*). The specified Critical Residual Biomass must be less than or equal to the Grazing Residual Target.
3. The model allocates animals to the grazing area with the highest amount of biomass if it is higher than the specified Critical Residual Biomass. Once animals are allocated to a grazing area, they remain in that grazing area until either the Grazing Residual Target (if biomass is higher than this level it becomes the default trigger) or Critical Residual Biomass (if biomass is between the two levels, then this becomes the default trigger) is reached. Livestock are then always moved to the next grazing area with the highest biomass.
4. When all grazing areas are below the Grazing Residual Target, they continue to be rotationally grazed using the Critical Residual Biomass. When all grazing areas are below the Critical Residual Biomass all animals are automatically moved into the Warm Shed/Pen. Here they are assumed to be fed the specified supplementary feed available to the herder.
5. Once grassland biomass returns to the Critical Residual Biomass, animals are moved out of the warm shed/pen and into the grazing area with the highest biomass available, and continue rotating through grazing areas as detailed in points 3 & 4.
6. The user can specify the quality of the warm shed/pen given its expected capacity for maintaining higher temperatures, reducing the wind speed experienced by animals and whether or not animals are exposed to rainfall.

[10] Supplementary feeding does not automatically occur when animals are selected to be in the Warm Shed/Pen overnight only. Under these conditions, animals are only fed if minimal body condition score or grassland biomass trigger feeding during the specified supplementary feeding period.

7. While animals reside within the warm shed/pen, they are assumed to be fed the specified supplementary feed available to the herder. When animals are grazing, they are offered supplements based on the specified supplementary feeding rules, and can also be housed in the warm sheds/pens overnight if this option is selected.

3.4.3 Grassland consumption sub-model

The differences in quality between the desirable and less-desirable species components of the grassland and their impact on livestock production have been estimated through selective grazing. This has resulted in more or less dry matter being consumed from either species group depending on their relative availability and quality, as well as accounting for the substitution effect from the feeding of any supplements on reducing grassland dry matter intake.

The grassland consumption from the desirable and less-desirable components of the sward is assumed to be evenly distributed throughout the grazing area depending on the weighted consumption from the quality pools and the proportion of the grazing area occupied by desirable and less-desirable species groups. Grassland consumption from each individual sward component is calculated as:

$$PC_U = \sum_{dp=1}^{6} YC_{dp} PYP_{Udp} \text{ and } PC_D = \sum_{dp=1}^{6} YC_{dp} PYP_{Ddp} \quad (25)$$

where YC_{dp} is the total quantity of grassland consumed per hectare from each digestibility pool (kg DM/ha) with desirable and less-desirable sward components combined, PYP_{Ddp} and PYP_{Udp} are the area-weighted proportion of dry matter in each digestibility pool for desirable and less-desirable sward components.

The quantity of grassland consumed from each digestibility pool, YC_{dp}, is a function of relative intake from each pool, stocking rate and grassland dry matter consumption per grazing sheep.

$$YC_{dp} = DMI_P SR \left(\frac{RI_{dp}}{\sum_{dp=1}^{6} RI_{dp}} \right) \quad (26)$$

where DMI_P is the total grassland dry matter intake (kg/hd/d), SR is the stocking rate (hd/ha), and RI_{dp} is the relative intake from each of the grassland digestibility pools. The individual area-weighted proportion of dry matter existing in each of the digestibility pools is calculated as follows:

$$PYP_{U\,dp} = \frac{GU_{dp}}{\sum_{dp=1}^{6} GU_{dp}} \text{ and } PYP_{D\,dp} = \frac{GD_{dp}}{\sum_{dp=1}^{6} GD_{dp}} \quad (27)$$

where GU_{dp} and GD_{dp} are the quantities of grassland dry matter (kg DM/ha) in each of the digestibility pools for less-desirable and desirable sward components.

The proportional distribution of biomass to each of the digestibility pools, GU_{dp} and GD_{dp}, is based on a modification of the equations described by Freer et al. (2012). The alternative model adapted here allocates the proportion of dry matter (kg DM/ha) within each of the 6 digestibility pools (DMD pools of 0.8, 0.7, 0.6, 0.5, 0.4, 0.3) so that a mean weighted DMD of the desirable and less-desirable components is equal to the separately nominated DMD for each component. Both GU_{dp} and GD_{dp} are calculated using the same distribution function, G_{dp}, as follows and shown in Figure 3.8:

$$G_{dp} = [x^5 \quad 5x^4(1-x) \quad 10x^3(1-x)^2 \quad 10x^2(1-x)^3 \quad 5x(1-x)^4 \quad (1-x)^5] \quad (28)$$

where $x = \frac{DMD_{nom} - 0.3}{0.8 - 0.3}$, and DMD_{nom} is the nominated mean dry matter digestibility of the sward functional group. Although this empirical approach is a simplification of more mechanistic approaches that account for leaf:stem ratios etc., it does provide consistent results with those field experiments which have shown that even under a broad range of grazing intensities (and subsequent DM availability), grazing animals, particularly sheep achieve similar dietary dry matter digestibility, even though animal performance varies in response to biomass availability within an extensive grazing system (Müller et al., 2014).

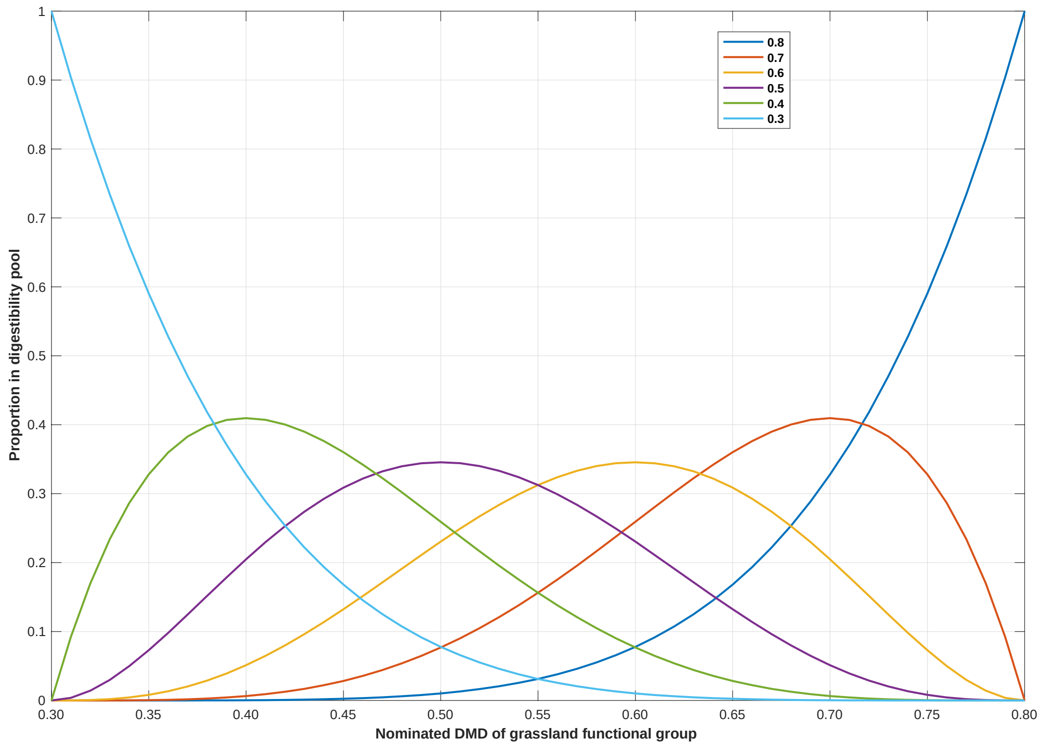

Figure 3.8: The proportion of grassland biomass allocated to each of the six digestibility pools (DMD pools of 0.8, 0.7, 0.6, 0.5, 0.4, 0.3), in relation to the nominated mean dry matter digestibility (DMD) of the grassland functional group.

3.5 Modelling household economics

To understand the expected economic and financial performance of herder households, a whole farm system approach is required. Typically, the economic analysis of farming systems in this type of research has only considered the analysis to a gross margin level and typically on a unit area basis. Although this provides useful information on the variability of enterprise returns, it provides little information on the impact of such variability on whole farm system performance. A whole farm system approach considers the cumulative effect of enterprise and system performance on a herder's cash flow, profitability and wealth over the long-term.

The approach applied in the *StageTHREE* SGM follows the standard method of analysing whole farm financial and economic performance described in Behrendt et al. (2014) and Malcolm et al. (2005). The whole farm financial and economic sub-model operates at a daily, annual and planning horizon time-step. It utilises the biophysical outputs to calculate enterprise income, cash costs and gross margins. The cumulative net flows of cash from enterprises (i.e. net of variable costs) and enterprise assets then interact with whole farm fixed and financial costs, and assets and liabilities, to determine a range of financial key performance indicators that measure profitability, efficiency and viability (Table 2). Daily cash inflows and outflows are then extracted (including the value of initial capital invested by herders and its salvage value, which predominantly represents livestock assets and small plant and equipment) to undertake the economic analysis of the farming systems through commonly used investment analysis techniques, such as Net Present Value.

Table 2: Key variables used to assess financial and economic performance.

Economic Impact	Variables reported
Enterprise profitability	Enterprise gross margin returns and variability
	Cumulative enterprise cash flow
Whole farm profitability	Cumulative cash balance
	Household cash flow
	Annual cash flow
	Operating Profit[11]
	Net Profit[12]
	Return on assets (ROA)[13]
	Return on equity (ROE)[14]
	Equity (Total Assets less Total Liabilities)
	Equity percentage (Net Wealth / Total Assets)
Investment performance	Net present value (NPV)
	Internal rate of return (IRR)
	Modified internal rate of return (MIRR)
	Net present value as an annuity (NPVa)
	Accounting Rate of Return (ARR)[15]

To provide insights into both household financial and economic measures that may be of interest to herders and policy makers alike, the *StageTHREE* SGM reports and aggregates economic data at multiple levels. At the herder household level, the Operating Cash Margin

[11] Operating Profit (Earnings Before Interest and Tax) is based on management accounting principles, not tax compliance.

[12] Net Profit is Operating Profit less the costs of finance. Taxation liabilities are not included in this analysis.

[13] ROA = Operating Profit (Earnings Before Interest and Tax) / Annual Mean Assets

[14] ROE = Net Profit / Annual Mean Equity

[15] Accounting Rate of Return (i.e. Simple Rate of Return) is the average Operating Profit for the entire simulation divided by the total initial investment (i.e. the starting total assets).

(OCM) represents the cash flow of a herder household before the costs of any financing are considered (i.e. they are assumed to be at full equity) and may be aggregated at different time-steps (e.g. annual) to indicate operating cash flow variability. Any volatility in the OCM represents 'business risk' and accounts for any variability in the production of outputs, the use of inputs, and their respective values. Key assumptions in the derivation of the OCM, is that it allows for both the cost of the herder's family labour (either as an opportunity cost or as personal expenses which may include items such as education, medical and other household expenses) and the cost of owning machinery[16].

Whole farm financial and economic performance is analysed on both an annual and multi-year basis. Each simulation is initiated using a common opening balance sheet (i.e. consistent opening assets and liabilities between all simulations of a specified farming system), into which the OCM is integrated to produce net cash flows, Profit & Loss and Balance Sheet statements. Any potential costs of financing the herder household through the cash account, as well as the existing liabilities, is calculated and incurred sequentially at a daily time-step.

Additionally, any subsidy payments or other income received also adds to the cash flow of the whole system. From this data, further measures of both herder household financial performance and system economic performance can be examined at annual (e.g. returns on assets or equity) or planning horizon time-steps (e.g. Net Present Value as an annuity from Nuthall (2016) or Modified Internal Rate of Return from Barry et al. (1999)). At this whole farm system level of analysis, the variability in outcomes accounts for both 'business' and 'financial' risk, and can provide insights into whole system economic performance for policy planning and the testing of different strategies on system performance.

3.5.1 Incorporation of risk

All producers of agricultural products are exposed to exogenous variables that influence their profitability. The natural phenomenon of climate variability exposes producers to production risk, and market fluctuations expose producers to economic risk (Antle, 1983). Much of the literature regarding the choice between risky alternatives in agricultural production is oriented towards 'expected utility theory' (Hardaker et al., 2002; Rae, 1994). This assumes that producers will aim to maximise their personal satisfaction or 'expected utility' based on their personal utility function, which depends on their level of risk aversion. Antle (1983) suggests that,

[16] The base assumption is that herders/farmers cannot 'live off' the depreciation of their depreciable assets, and a cash allowance is made in the cash flow for the replacement of depreciating assets.

because risk affects the economic efficiency of all producers, regardless of their level of risk aversion, dynamic risk-neutral models are more useful than static risk-averse models for understanding the role of production risk in decision making.

A method which does not require assumptions of risk aversion levels to be made, is applied to the long run Monte Carlo simulations of the *StageTHREE* SGM. Different combinations of technologies and management strategies are evaluated based on expected returns and risk (the variability of returns). In this case, the risk (climate and output price risk) is non-embedded in the decision making process as the results of the simulations describe the risky consequences of the decisions applied before any risky states occur.

4 Data requirements – quick reference inputs and parameters required[17]

Inputs	Units	Notes
Geographic information		
Latitude of case study region	°	Negative value in southern hemisphere, positive in northern hemisphere
Altitude above sea level for case study area	m	
Weather information (must be loaded before model can RUN)		
Daily mean Air velocity	m/s	Requires one year or more years of corresponding data. Model will linearly interpolate any missing daily data.
Daily minimum ambient air temperature	°C	Requires one year or more years of corresponding data. Model will linearly interpolate any missing daily data.
Daily maximum ambient air temperature	°C	Requires one year or more years of corresponding data. Model will linearly interpolate any missing daily data.
Average daily ambient air temperature	°C	Requires one year or more years of corresponding data. Model will linearly interpolate any missing daily data.
Daily rainfall	mm/d	Requires one year or more years of corresponding data. Model will linearly interpolate any missing daily data.
Daily Relative humidity		Absolute (whole number) or % is workable. Requires one year or more years of corresponding data. Model will linearly interpolate any missing daily data.
Soil Information		
Slope of grazing areas in degrees	°	
Starting available soil water on first day of simulation (gravitational)	0-1	Estimated via inverse modelling to identify reasonable initial conditions. Use 'Calculate' button to provide guidelines for gravimetric Wilting Point and Field Capacity.
Proportion sand content in soil	0-1	
Proportion clay content in soil	0-1	
Proportions of soil sand fractions	0-Sand	Default values assume 0.246 Very Fine Sand (50-100um), 0.246 Fine Sand (100-250um), 0.169 for medium (250-500um), coarse (500-1000) and very coarse (>1000um) sand
The gravimetric soil water content	%	At 15 bar matric potential. Default value 40
Bulk Density	g/cm^3	Default derived from Sand & Clay content
Field Capacity	g/g	Default derived from Sand & Clay content
Wilting Point	g/g	Default derived from Sand & Clay content

[17] Grey text refers to inputs and parameters that are adjustable, but not essential to operate the model, as they are derived through default values and/or functions. Fixed parameters, some of which can also be modified in the Matlab open access version, are listed in Appendix A.
DOY refers to Julian day, with 1 Jan = 1.

Effect of excess soil water on growth limiting factor	0-1	Waterlogging effect on max growth. Default value of 0.3
Soil Depth – effective rooting depth	mm	Rooting depth
Proportion of field capacity where plant growth becomes constrained	0-1	Represents the point below which plants become water stressed (mi<1)
Snow Depth at DOY1	mm	Model automatically calculates a mean snow depth from historical weather data as it is being uploaded, and inserts that value as the starting assumption. If uploading a Parameter Template, this value will be overwritten with that noted in the template.
Soil Fertility Dynamics		'On' uses the existing relationship between soil erosion and soil creation, and the expected soil nutrient loss or gain based on that described by Sharpley (1985) which influences the soil fertility index, FI_S (eqn. 10). 'Off' keeps soil fertility constant throughout all years and simulations.
Grassland information		
Soil Temperature Threshold for plant growth	°C	Soil Temperature Threshold below which grassland growth is inactive/limited, or below ground biochemical processes are limited
Minimum Temperature for plant growth	°C	Minimum ambient air temperature for plant growth to occur. Based on Nix (1981)
Optimal Temperature for plant growth	°C	Optimal ambient air temperature for plant growth. Based on Nix (1981)
Maximum Temperature for plant growth	°C	Maximum ambient air temperature for plant growth – beyond which no growth occurs. Based on Nix (1981)
Maximum leaf canopy height of grassland	cm	Default value of 30cm (a value of 50cm is suggested for perennial ryegrass, based on Johnson (2013))
Leaf Area Index at half maximum canopy height	m^2/m^2	Default value of 2 m^2 leaf/m^2 ground applies to perennial ryegrass, based on Johnson (2013)
Canopy extinction coefficient	0.5-1	Default value (0.6 – based on a grass dominated sward; 0.5 is typical for cereals & grasses, increase this up to a value of 1.0 for perfectly horizontal inclined leaves - e.g. 0.8 for clovers)
Proportion of legumes in the grasslands	0-1	Needs supporting field data
Predominant species type		'C3' or 'C4' species. Influences the *g* value for predicting relative ingestibility (Freer et al., 2007) and stomatal conductance of the sward which is part of the soil water balance model (Johnson, 2013).
Monthly desirable Dry Matter Digestibility (DMD)	0.3-0.8	Nominated values for the dry matter digestibility of desirable species - Needs Field Data
Monthly less-desirable DMD	0.3-0.8	Nominated values for the dry matter digestibility of less-desirable species - Needs Field Data
Grassland growth curve - alpha	0-1	Derived through calibration - Needs Field Data for both desirable and less-desirable species/functional groups
Grassland growth curve – gamma	1-2	Derived through calibration – Needs Field Data for both desirable and less-desirable species/functional groups
Grassland Growth curve – Ymax	Kg DM/ha	Can be derived through calibration or literature/expert opinion for each species/functional group

(maximum biomass limit to grassland growth)		
Maximum rate of biomass decay for desirable and less-desirable groups/species	0-1	Ratio of maximum daily dry matter decay – maybe derived from repeated measures of biomass throughout a year
Grassland Dynamics		'On' uses the prescribed parameters to included grassland botanical composition change in simulations. 'Off' keeps initial grassland composition constant throughout all years and simulations.
Change in the proportion of space occupied by desirables over time under grazing rest	0-1	Derived through estimation of the expected time (years) to move from an initial proportion to a maximum proportion under complete grazing rest. To calibrate with data requires annual measures of functional group biomass in ungrazed grasslands over more than one year.
Impact coefficient of Livestock on desirable proportion	0-1	Derived through calibration. Requires measured changes in, botanical composition, desirable and less-desirable biomass, and stocking rates (SE/ha) over more than one year. Default value (0.272)
Management calendar		
Time based grazing – Minimum days spent in each grazing area	days	Select this option to use time (days) based grazing rules. For all grazing areas with >0ha, the 'Grazing Days (max)' must be greater than 1 day. First grazing area is default starting area in the rotation, and rotation follows sequence of listed grazing areas.
Biomass based grazing – Critical Residual Biomass	Kg DM/ha	Set this residual for biomass based grazing rules. The grazing area with maximum biomass above this critical minimum target is grazed first and continues to be grazed until reaching the 'Critical Residual Biomass', after which animals are moved to the next grazing area with the maximum biomass. Destocking of all grazing areas into a warm shed/pen will occur when all grazing areas have less than the specified critical residual biomass.
Biomass based grazing – Grazing Residual Target	Kg DM/ha	Set this target for biomass based grazing rules. If grazing areas achieve a biomass above the 'Grazing Biomass Target', the rotation of animals is controlled by this more optimal minimum residual target. i.e. animals are moved to next grazing area with the maximum available biomass, once biomass reduces to this target. If no grazing area maintains biomass in excess of the 'Grazing Residual Target', the 'Critical Residual Biomass' and rules are used instead.
Size and name of each grazing area	Ha	Grazing areas with 0 Ha are ignored by the model. Up to 30 grazing areas may be modelled.
Starting biomass of desirables in each grazing area on first day of simulation	kg DM/ha	Estimated via inverse modelling to identify reasonable initial conditions.
Starting biomass of less-desirables in each grazing area on first day of simulation	kg DM/ha	Estimated via inverse modelling to identify reasonable initial conditions.
Initial Area proportion of desirables in each grazing area	0-1	Needs Field Data at species or functional group

Initial Area proportion of less-desirables in each grazing area	0-1	Needs Field Data at species or functional group
Selling assumptions for females and progeny males in each age cohort	0-1	Minimum culling rates of females and progeny males in each cohort. Breeding males (rams/bulls) are automatically sold & purchased to maintain sufficient numbers.
Animal sale dates of females, progeny and breeding males in each age cohort	DOY	
Young Animal Selling Rule	Kg Lwt	Select this option to allow the model to sell young animals (<12mths of age), based on the prescribed selling proportions, prior to the specified selling DOY if they reach the specified Target Sale Weight (kgs liveweight). Ensure weaning occurs prior to any sales.
Animal purchase date for breeding males	DOY	
Lambing and calving date	DOY	Base on the expected median birth date for the flock/herd.
Lactation duration	DOY	Number of days after lambing or calving date while in lactation
Wool or hair harvesting day (shearing)	DOY	For all animal types.
Warm Shed/pen		Select option to force animals into warm shed/pens for nominated periods of time under Time (Day) based grazing. This is controlled by 'DOY into Warm shed/pens' and 'DOY turned out from warm shed/pens'. Can also be used only overnight.
Minimum Temperature Gain	°C	Expected temperature gain above that of external ambient air temperature from animals being confined to a warm shed/pen. Influences maintenance energy requirements due to cold (ME_{cold}).
Wind Reduction	%	Expected reduction in wind speed from animals being confined to a warm shed/pen. Influences maintenance energy requirements due to cold (ME_{cold}).
Rainfall Exclusion		Select this option if animals are protected from precipitation through roofing while being confined to the warm shed/pen. Influences maintenance energy requirements due to cold (ME_{cold}).
Animal information		
Extra daily travel distance	klm	Distance from overnight pen/shed to grazing area in grassland and return.
Livestock Type		Option to select species type, being either Sheep/Goats (either a wool/fibre type producing breed (e.g. Merino) or a meat producing breed (e.g. British/Euro type breeds)), Cattle or Yaks. Must adjust all livestock parameters (e.g. SRW) to reflect selected species. This adjusts fixed parameters that influence all facets of growth, fecundity, reproduction and lactation.
Standard Reference Weight	kg	Weight of mature animals (females) in average condition (CS3). Adjust for each livestock type.
The normal expected birth weight of an animal	kg	Adjust for each livestock/species type. Default value changes for animal type, e.g. Wool sheep value of 3.3kg Lwt is default.
Opening numbers of females and male	head	The unweaned animals are all included under the females in the <12 months age cohort. The number of total females is

progeny in each age cohort		maintained unless user specifies a new target number of females via the 'Simulation & Outputs' tab.
Fecundity in each cohort	0-1	Animals born per joined female (age cohorts with individual rates). Approximate initial value is corrected post DOY 1 of simulation.
Assumed initial proportion of animals born as twins & triplets	0-1	Default of 0.25 for twins and 0.05 for triplets (sheep) on DOY 1 for first day of simulation only.
Joining rate	0-1	Number of breeding males per female
Basal mortality rate	0-1	Minimum proportion of deaths per annum
Starting live weight of females, male progeny in each age cohort	kg	On DOY = 1 of simulation. Derived through inverse modelling to provide a reasonable estimate of initial liveweights for each animal class and age cohort.
Young Animal Selling Rule	Kg Lwt, DOY	Select this option to engage an alternative selling rule, where young animals (<12months of age) are sold at either the target sale weight (kg Lwt) or 'DOY Sold', whichever comes first.
Wool/hair production (wool for sheep, hair for yaks/cattle/goats)		
Standard Fleece/Fibre Weight (greasy)	kg/hd	3-4 year old female or castrated male, breed specific. Should be included for Cattle and Yaks to ensure thermal capacity of hair is modelled (but set harvest costs and sale price to 0 if not harvested).
Adult Wool/Fibre diameter	µm	3-4 year old female or castrated male, breed specific. Should be included for Cattle and Yaks to ensure thermal capacity of hair is modelled.
Standard Fleece Length	cm	12 months fleece length for a 3-4 year old female or castrated male, breed specific. Should be included for Cattle and Yaks to ensure thermal capacity of hair is modelled (e.g. 3cm coat for cattle).
Photoperiod effect on wool growth	0-1	Default values for animal type & breed type
Clean:Greasy ratio for wool/fibre	0-1	The clean yield of harvested wool or hair.
Carry over fleece length post shearing	cm	Default value (1 cm)
Default harvestable fleece weight at birth	kg	Default value (0 kg)
Starting wool quantity	Kg/head	Default function based on time of harvest, age and Standard Fleece Weight
Default fibre diameter of females, male progeny, and breeding males in each age cohort	µm	Default function
Supplementary feeding		
Starting day for supplementary feeding	DOY	Enables the initiation of supplementary feeding rules
Ending day for supplementary feeding	DOY	Ends the application of supplementary feeding rules
DMD of supplement feed	0.3-0.9	Specify Dry Matter Digestibility of supplements offered to livestock.
Ether extract value for supplement	g/kg	

DM:Wet weight ratio for supplements	0-1	
Defined ration per head (adult)	kg wet/head/ day	Represents the amount of supplement offered to livestock at their Standard Reference Weight. If feeding rules only occur at condition scores different from a CS of 3.0, may need to proportionally adjust this value.
Defined relative condition target for initiating supplementary feeding for each age cohort in females, progeny & breeding males	0-1	Relates to condition score (1 = CS3; 0.85 = CS2; 0.7 = CS1). These rules are applied during the specified Start and End DOY for supplementary feeding.
Defined minimum grassland biomass threshold for initiating supplementary feeding	kg DM/ha	This rule is applied during the specified Start and End DOY for supplementary feeding
Economic inputs[18]		
Carcass: Liveweight Ratio	0-1	For all classes and age cohorts of livestock
Sale Prices	C/kg Cwt	For all classes and age cohorts of livestock
Sale Price Standard Deviation	C/kg Cwt	For all classes and age cohorts of livestock, the expected standard deviation of sale prices. Set to 0 for no meat price risk.
Purchase Price	C/hd	For all classes and age cohorts of livestock
Skin Price	C/hd	For all classes and age cohorts of livestock
Wool/Fibre Price	C/kg	C/kg clean fibre/wool
Wool/Fibre Price CoV	≥ 0	Coefficient of Variation for Wool/Fibre prices. Set to 0 for no wool/fibre price risk
Enterprise Variable Costs	C/hd, /ha, /kg	For each livestock enterprise type, with DOY occurring defined
Herder Family Costs (including opportunity costs of labour)	C/yr	Cash cost which is allocated daily.
Herder Fixed costs	C/yr	Cash cost which is allocated daily.
Herder equipment replacement value & expected life	C & yrs	The replacement value and expected life determines the annual cost of owning any machinery or depreciable infrastructure. The annual cost of ownership is included in the cash flow.
Interest Rate for any borrowed money	%	Per annum % equivalent if cash account is in debit
Interest Rate for any saved money	%	Per annum % equivalent if cash account is in credit
Real Discount Rate (r)	%	If unknown, can be estimated through the expected inflation rate (*f*) and Interest rate for saved money (*m*, assuming this is similar to a risk-free rate of return), such that $r = (m - f)/(1 - f)$.
Subsidy Payments received	C	Total amount of Subsidy payments received annually and allocated daily in cash flow
Other Income received	C	Total amount of other income received annually and allocated daily in cash flow

[18] C stands for local currency

Cost of any proposed capital purchases	C	Up to two items can be planned for. All capital purchases are assumed to be financed through the cash flow.
Amount owing, Interest Rate, Term and repayment frequency for any borrowed money	C, %, Yrs, n	Up to two loans can be included.

5 Model Calibration

The primary focus of model calibration option is the estimation of parameters that drive grassland growth. All of the parameters on the ***Soil & Grasslands Input*** tab determine pasture growth and quality within and between years. The model then uses a three-tier discrete grid search approach to parameter estimation (Jiménez et al., 2007). It searches a grid of pre-determined parameter space for α

The steps to calibrating the grassland growth sub-models are as follows:

1. Prepare experimental/field or published data in an excel spreadsheet[20] such that:
    a. Column 1: Sampling dates as a serial number
    b. Column 2: Corresponding biomass data for Less-desirables (kg DM/ha)
    c. Column 3: Corresponding biomass data for Desirables (kg DM/ha)
    d. This data can span both seasons and years, however, corresponding full year daily climate data must be uploaded into the model prior to any calibration runs.
2. Upload climate data that spans at least the uploaded experimental data. For guidelines on minimum daily climate data requirements, see guidelines on page 37. Each time weather data is loaded, the model produces a climatology chart showing annual mean variation in minimum and maximum air temperature, box plots for monthly rainfall, and an annotation indicating the long-run average annual rainfall for the location and uploaded data. During this process the expected snow depth on DOY1 will also be

[19] The calibration process tests combinations of α_G and γ_G values at discrete increments of 0.1, 0.01 and 0.001 in succession between 1) the initial boundaries of these parameters (α_G values are constrained to between 0-1, and γ_G values between 1-2), then 2) ±0.1 of parameter combination set identified during step 1 that minimises the RMSE, and finally 3) ±0.01 of the parameter combination set identified during step 2 that minimises RMSE, respectively.

[20] An example is provided in the included file called 'Grassland_Sample_Data.xslx'. The best calibrations occur when multiple time-distributed measures (observed data) are available over 1-2 years. Single annual measures over many years often provide poor model predictions and calibration.

calculated and loaded into the model (this will be replaced if a parameter template is uploaded – next step, so best to record the value and include it in the parameter template).

3. Upload any existing Parameter values that may exist in the Parameter Excel spreadsheet (see included Parameters_Template for Sheep or Cattle, or section on Parameter Exports on page 54).
4. On the ***Calibration*** tab, use the 'Load Experimental data' button to upload your data. This needs only to occur once prior to the first calibration run.
5. Modify all site-specific parameters as required to expected values on all tabs within the model, primarily the ***Instructions***, ***Soil & Grassland Input***[21], ***Grazing Area Input*** and ***Livestock Input*** tabs. Livestock may be grazed and best efforts should be made to match model process and parameters to those that represent the conditions under which the experimental/field data was obtained[22]. Only the first listed grazing area is used for the calibration process, which also uses the initial proportions of desirable and less-desirable species to transform measured biomass into spatially adjusted biomass densities[23]. The calibration process will identify the optimal Growth parameter alpha and Growth parameter gamma for both less-desirable and desirable species/functional groups (Equation 10, page 14: α_G and γ_G).
6. On the ***Instructions*** tab check the box to select 'Growth Calibration'. Selecting this option switches the model to calibration mode. The model will run between the specified years under the 'Deterministic… between years…' option. <u>Users need to ensure the selected years match the uploaded experimental/field and weather data.</u>
7. On the ***Simulation & Outputs*** tab press the 'RUN' button. The model will firstly test for and identify optimal alpha and gamma values, and then use those parameters to

[21] If no grassland composition data is available, it may be more appropriate to turn-off Grassland Dynamics so the model maintains a constant composition throughout the simulation period.

[22] If experimental data is from un-grazed treatments, maintain a minimal number of animals and a very large grazing area (e.g. 100hd over 10,000 hectares) and constrain animals to warm shed/pen all year (from DOY1 to 365) - the model cannot run without livestock.

[23] That is, measured biomass (kg DM/ha) is divided by the indicated spatial occupation of the species group. E.g. grassland cuts reveal a mean measurement of 200kg DM/ha for less-desirable, and 400kg DM/ha for desirable species (a total of 600kg DM/ha), the spatial occupation (proportion) is indicated as 0.3 and 0.7 for less-desirable and desirable. In the model, this means the spatially adjusted biomass density of less-desirable and desirable is 666kg DM/ha (200kg DM/ha ÷ 0.3, in this case with a very erect growth habit) and 571kg DM/ha (400kg DM/ha ÷ 0.7, in this case with a more prostrate growth habit compared to the less-desirable group), indicating the less-desirable species tend to be larger but more scattered plants in this case.

produce a simulation run between the specified years. To identify the parameter values, model goodness of fit is assessed by calculating and identifying the lowest simulated root mean square error (RMSE). The model also reports the R^2 of the Observed Vs Predicted plot. The process also uses a stepwise Bayesian procedure to focus parameter estimates on global optimum values identified through a three-stage iterative process. Optimal parameter values are automatically uploaded into the ***Soil & Grassland Input*** tab and model accuracy is reported on the ***Calibration*** tab. The model will also produce the normal suite of diagnostic charts under the identified optimal parameter values, including charts that indicate the degree of model accuracy (Observed vs Predicted; Observed biomass vs time-series of grassland biomass), and the sigmoidal growth curves when the Growth Index =1.0. If not sufficiently accurate, modify any model parameters and 'RUN' again (see 5.1 Tips for calibrating the model).

8. Once satisfied with model performance, use the 'Export Parameters' button on the ***Simulation & Outputs*** tab to record a copy of your parameter combination (as described in section 6.3). Data from the final simulation run will also be available for exporting via the 'Export Data' button (as described in section 6.1).
9. Remember to uncheck the 'Growth Calibration' option on the ***Instructions*** tab prior to performing any non-calibration runs of the model.

5.1 Tips for calibrating the model

1. There is a strong interaction between the parameter values for Maximum Biomass Decay (proportion/day) and the resulting shapes of growth curves and inter-seasonal fluctuations in grassland biomass. Typical values for this parameter tend to be around 0.015 to 0.025 (or higher) for high DMD species/functional groups with high leaf:stem biomass ratios, and <0.015 for species/functional groups with low leaf:stem biomass ratios. If the sigmoidal growth curves or the time-series biomass fluctuations in observed v predicted values does not match expectations, consider testing different rates of biomass decay. Likewise, *Mean* Y_{max} values also somewhat influence the shape of the growth curves, although the outcomes are not as sensitive to this parameter.
2. To modify the expected fractional ground cover and canopy height interactions (leaf height), which also influence the amounts of wind and water induced soil erosion, consider adjusting the maximum canopy height (H_{max}), leaf area index at half maximum

height (LAI_{half})[24] and canopy extinction coefficient (CEC)[25]. This can be more easily estimated using corresponding field data on canopy height and fractional ground cover. Figure 5.1 provides an example for the Mongolian desert steppe where field data indicated that at a grassland canopy height of around 5cm, corresponding fractional ground cover would be around 30%, and logically this would occur at the same LAI, in this case assumed to be a LAI of around 0.5. Interactions between different LAI_{half}, CEC and H_{max} settings can be explored using the 'Test Canopy Dynamics' button on the ***Soils & Grasslands Input*** tab.

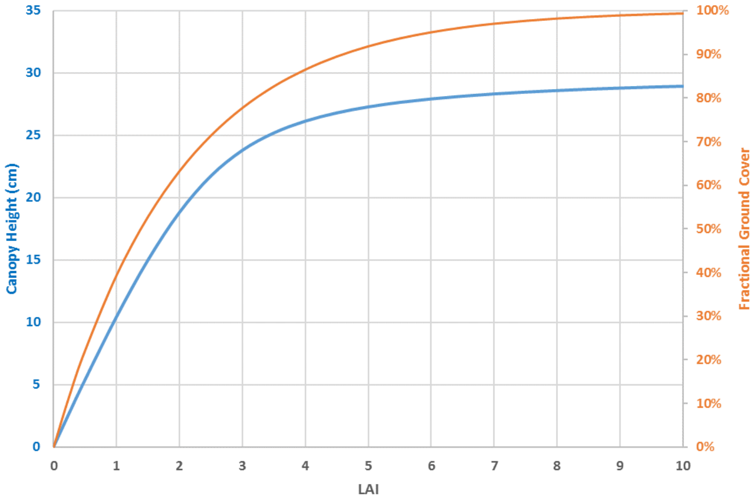

Figure 5.1: Relationship between canopy height (blue line) and fractional ground cover (orange line) in response to LAI. Model settings are LAI_{half} = 1.5, H_{max} = 30cm and CEC = 0.5.

3. To modify the timing of the start and peak of growing seasons, consider adjusting the soil temperature threshold, as well as the minimum, optimal and maximum temperatures for growth.
4. If modelling a grassland that has already suffered from many years of soil erosion, and thereby the majority of soil nutrients have already been lost from the top soil (i.e. low SOC), then consider running the model with Soil Fertility Dynamics turned off, as this will keep the Soil Fertility Index constant at the starting level (i.e. FI_S = 1.0) for the entire simulation. This may resemble the actual systems more accurately, rather than the assumed more normal initial soil fertility levels in the model.

[24] For perennial ryegrass, the default value for LAI_{half} = 2.0. This value would vary significantly for different species or functional groups and the packaged file 'StageTHREE parameters.xslx' can assist with identifying appropriate values.

[25] Indicatively, the canopy extinction coefficient is 0 for bare ground/species with perfectly erect leaves, 0.5 for grasses/cereal crops, 0.8 for legumes such as clover, and 1.0 for species with perfectly prostrate leaves.

5. Similarly to soil fertility interactions, if there is no data to indicate rates of botanical composition change, consider turning off Grassland Dynamics to improve model accuracy. Turning this function off will result in constant botanical composition over the entire simulation.
6. Grassland quality, namely its monthly mean Dry Matter Digestibility, strongly influences animal performance on the grassland. It may be useful to modify specified DMD for each functional group, once grassland growth has been calibrated, to modify expected animal performance when biomass is known and animal parameters have been defined (e.g. SRW). However, if you are simulating a known stocking rate that is associated with the experimental biomass data, then be aware that supplementary feeding and grazing management rules will have significant interactions with effective grazing pressure and grassland consumption.

6 Model output

6.1 Simulation outputs

To archive the outputs form individual simulation runs, there is an export function embedded into the SGM. On the ***Simulation & Outputs*** tab in the model, there is an 'Export Data' button (Figure 6.1). When this button is pressed after a simulation has been executed and the graphics produced, two files are saved into the workspace:

1. An Excel spreadsheet file with the name 'OutputData_mm-dd-yyyy hr-min.xlsx'
2. A Matlab workspace file with the name 'Sim_Output.mat'

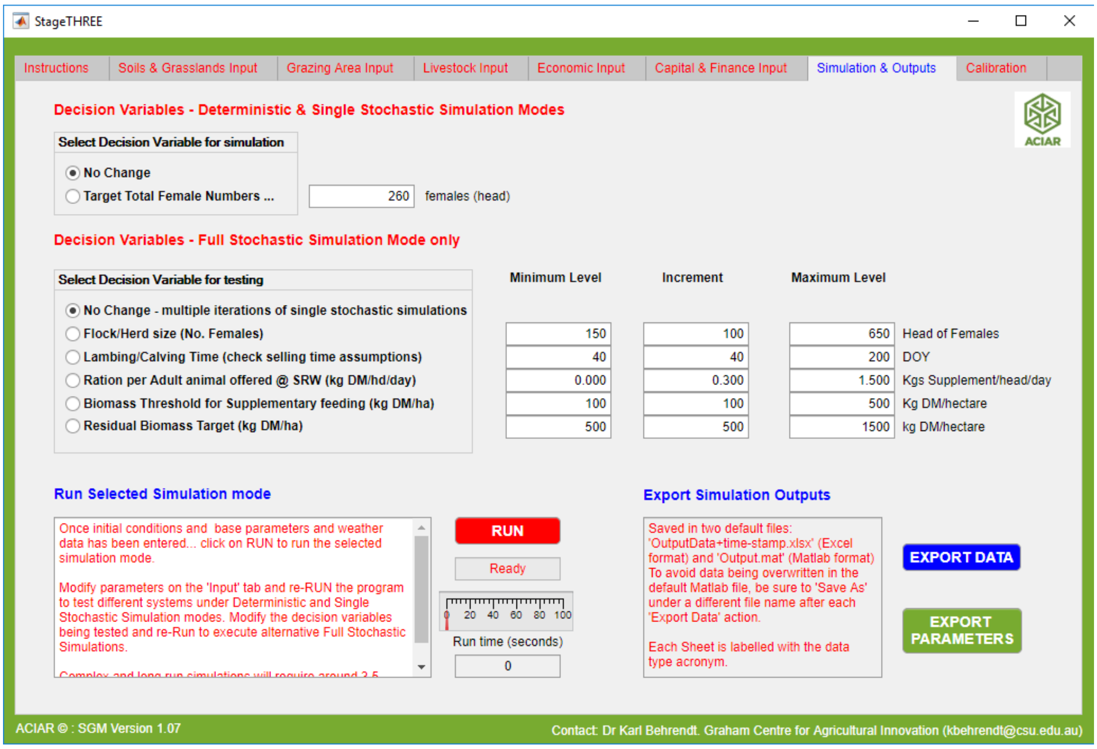

Figure 6.1: StageTHREE SGM *Simulation & Outputs* tab

The excel spreadsheet file allows multiple runs to be executed and saved sequentially, each with their own individual time stamp embedded within the file name. In each excel file, the first sheet is blank and allows for the recording of simulation details or input parameters. Subsequent sheets provide outputs for the variables shown in Table 3. Additional output variables can be stored and included upon request.

Table 3: Outputs available via exported excel and Matlab files

Acronym	Name	Description
NPVc	Net Present Value	This is the Net Present Value for a single iteration and is calculated using the user specified discount rate. It considers both cash inflows and outflows, as well as the initial capital investment by farmers/herders to reside in agriculture and the estimated salvage value of all agricultural assets at the end of the simulation period.
NPVa	Net Present Value as an annuity	NPVa is calculated from NPVc but as an annuity. It represents the NPVc as an equivalent annual value for the whole farm.
ACF	Annual Cash Flow	Net annual cash flow for the household after accounting for all cash expenses (including family+fixed costs, and any capital purchases), subsidies and other income in local currency.
AnimalGMha	Livestock Gross Margin	Annual gross margin per hectare for the livestock enterprise being run in the simulated system in local currency.
Methp	Methane Production	Total annual methane production from rumination (tonnes/year) for each iteration, year and test level.
MethEI	Methane Emissions Intensity	For each year, iteration and test level provides the annual methane emissions intensity for meat production (Kg CH_4 / kg carcass weight of meat).
Woolkg	Wool/Hair Production	Total annual wool/hair production in kilograms clean from the entire system, and for each iteration, year and test level.
Meatkg	Meat Production	Total annual meat production in kilograms carcass weight from the entire system, and for each iteration, year and test level.
ASWT	Average Sale Weight	Provides average selling weight, in order, for young females (<12mths age), adult females, young males (<12mths age), adult males, sire sales (i.e. 5 columns per test level). This is provided for each year of each iteration and test level.
HdSold	No. head sold	Provides number of animals sold, in order, for young females (<12mths age), adult females, young males (<12mths age), adult males, sire sales, as well as sires purchased (i.e. 6 columns per test level). This is provided for each year of each iteration and test level.
SoilL	Soil Loss	Total soil loss per annum from erosion due to both wind and water, and net of soil formation. It is reported for each grazing area (tonnes/hectare/year)
YGR	Pasture Growth Rate	In excel file for deterministic and single stochastic runs, it provides daily pasture growth rate (kg DM/ha/day) for each species group and grazing area. For full stochastic simulations, only average monthly growth rates are reported for each grazing area and species group (kg DM/ha/day) in excel files. Matlab files contain daily data (YGRd).
YGA	Grassland Biomass –	In excel file for deterministic and single stochastic runs, it provides daily amounts of biomass available (kg DM/ha) for each species group and grazing area. For full stochastic

	functional groups	simulations, only average monthly biomass amounts are reported for each grazing area and species group (kg DM/ha) in excel files. Matlab files contain daily data (YGAd).
GC	Ground Cover	In excel file for deterministic runs and single stochastic runs it provides the daily total combined average biomass per hectare for each grazing area, which includes the contribution of both desirables and less-desirables (tonnes DM/ha). For full stochastic simulations, only average monthly biomass is reported for each grazing area (tonnes/ha) in excel files. Matlab files contain daily data (GCd).
FGC	Fractional Ground Cover	In excel file for deterministic runs and single stochastic runs it provides the daily fractional ground cover for each grazing area. For full stochastic simulations, only average monthly fractional ground cover is reported for each grazing area (proportion of area covered with grassland vegetation) in excel files. Matlab files contain daily data (FGCd).
GH	Grassland canopy height	In excel file for deterministic runs and single stochastic runs it provides the daily average grassland canopy height for each grazing area (meters). For full stochastic simulations, only average monthly canopy heights are reported for each grazing area in excel files. Matlab files contain daily data (GHd).
ER	Erosion from Rainfall	In excel file for deterministic runs and single stochastic runs it provides the daily amount of soil erosion from rainfall for each grazing area (tonnes/ha/day). For full stochastic simulations, only total monthly amounts of soil erosion from rainfall is reported for each grazing area (tonnes/ha/month) in excel files. Matlab files contain daily data (ERd).
EW	Erosion from Wind	In excel file for deterministic runs and a single stochastic run it provides the daily amount of soil erosion from wind for each grazing area (tonnes/ha/day). For full stochastic simulations, only total monthly amounts of soil erosion from wind is reported for each grazing area (tonnes/ha/month) in excel files. Matlab files contain daily data (EWd).
XS	Proportion Desirables	Is the proportion of desirables in each grazing area at an annual time step. This is shown for each iteration with multiple simulations and test levels.
ConRate	Consumption Rate	Is the mean consumption rate of grassland dry matter (proportion of DM grown that is consumed by livestock) across all years of a simulation. This is shown for each iteration with multiple simulations and test levels.
LPVar	Livestock Price variation	Is the livestock price variance for each iteration and simulated year for each test level. It indicates the variance (+inf to –inf, centred on 0 – normally distributed random numbers) by which the meat price standard deviation is multiplied before being added to the user defined mean meat price in each year.

WPVar	Wool/Fibre Price variation	Is the wool/fibre price variance for each iteration and simulated year for each test level. It indicates the variance (+inf to –inf, centred on 0 – normally distributed random numbers) by which the wool/fibre price standard deviation is multiplied before being added to the user defined mean wool/fibre price in each year.
GSeasonSM	Growing Season Stochastic Multiplier	Is the Growing Season Stochastic Multiplier for each iteration and simulated year for each test level. It is an index that ranks the simulated year's total rainfall against the long term average total annual rainfall (which is derived from the weather data uploaded into the model).

6.2 Output Data Layout

The data is presented in the basic layout of iterations in rows (iteration count ascending downwards) and treatments in columns (based on selected decision variable and ascending left to right). More specifically the following forms exist:

- Whole system Data (e.g. NPVa, NPVc): Each Row contains the aggregated figure for a single simulation run (Iterations I_1... I_n), with each column representing a treatment (T_1... T_n). In a *Deterministic* and *Single Stochastic* run there will be only one data cell. Whereas for multiple iterations and multiple treatments under the *Full Stochastic Simulation*, each data point will represent an iteration x treatment combination.

	T_1	... T_n
I_1	Data	Data
... I_n	Data	Data

- Annual data (e.g. MethP, MethEI, Woolkg, Meatkg, ACF, AnimalGMha, LPVar, WPVar, GSeasonSM): Each row contains the aggregated annual figure for each of the simulation, with each column representing a treatment. In a *Deterministic* and *Single Stochastic* run there will be only one column of data showing the outcomes for each year simulated (Y_1... Y_n). For example, a system simulated for 10 years, the annual data will have a 10 rows x 1 column of data. Whereas for multiple iterations and multiple treatments under the *Full Stochastic Simulation*, each data point will represent an [iteration x year] x treatment combination, with iterations stacked downwards and treatment groups ascending to the right.

		T_1	... T_n
I_1	Y_1	Data	Data
	...Y_n	Data	Data
... I_n	Y_1	Data	Data
	...Y_n	Data	Data

- Annual or Daily Data across grazing areas (e.g. SoilL, GC, FGC, H, ER, EW): Each row contains the aggregated data (annual) or daily data for each simulation run, with each column representing a treatment x grazing area combination ($GA_1 \ldots GA_n$). In a *Deterministic* and *Single Stochastic* run there will only be one set of columns representing the different grazing areas showing the outcomes for each year or day simulated (i.e. two grazing areas simulated for 10 years – annual data will have a 10 rows x 2 columns of data; daily data will have 3650 rows and two columns of data). Whereas for multiple iterations and multiple treatments under the *Full Stochastic Simulation*, each data point will represent a [iteration x year] x [grazing area x treatment] combination, with iterations stacked downwards and treatment groups ascending to the right.

		T_1		… T_n	
		GA_1	… GA_n	GA_1	… GA_n
I_1	Y_1	Data	Data	Data	Data
	…Y_n	Data	Data	Data	Data
… I_n	Y_1	Data	Data	Data	Data
	…Y_n	Data	Data	Data	Data

A similar structure is used ASWT and HdSold. Instead of GA's, 5 and 6 columns are used for ASWT and HdSold respectively for each test level.

- Annual Data across grazing areas and grassland functional groups (e.g. XS, ConRate, YGR, YGA): Each row contains the data (annual, monthly or daily) for each simulation run, with each column representing a treatment x grazing area x functional group combination. In a *Deterministic* and *Single Stochastic* run there will only be one set of columns representing the different grazing areas and the two functional groups (less-desirable (*L-D*) and desirable (*D*)) showing the outcomes for each year simulated (i.e. two grazing areas simulated for 10 years – annual data will have a 10 rows x 4 columns of data (2 functional groups x 2 grazing areas). Whereas for multiple iterations and multiple treatments under the *Full Stochastic Simulation*, each data point will represent a [iteration x year] x [functional group x grazing area x treatment] combination, with iterations stacked downwards and treatment groups ascending to the right.

		T_1				... T_n			
		L-D		D		L-D		D	
		GA_1	... GA_n	GA_1	... GA_n	GA_1	... GA_n	GA_1	... GA_n
I_1	Y_1	Data	Data	Data	Data	Data	Data	Data	Data
	...Y_n	Data	Data	Data	Data	Data	Data	Data	Data
... I_n	Y_1	Data	Data	Data	Data	Data	Data	Data	Data
	...Y_n	Data	Data	Data	Data	Data	Data	Data	Data

6.3 Parameter Exports

The final tab, *Simulation & Outputs*, of the model provides an 'Export Parameters' button (Figure 6.1). When this button is pressed after a simulation has been executed and the graphics produced, an Excel spreadsheet file is saved into the models workspace with the name 'Parameters_mm-dd-yyyy hr-min.xlsx' , which includes a date and time stamp.

The excel spreadsheet provides all of the user defined parameters. It excludes any selected option buttons (e.g. Predominant species group, Grassland Dynamics etc), but includes all other assumptions. On the first sheet of the excel spreadsheet are the base parameters, and on the second sheet is the table summarising the grazing area data (including names, initial states and grazing days (max)). Please make note of your selected options but do not move any cells or insert/delete rows or columns, as this may lead to errors if the parameters are imported back into the model at a later time.

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8 Appendices

Appendix A : StageTHREE SGM release notes

V1.08 (July 2020)

1. Addition of a process to upload parameter sets, and the provision of two example parameter sets, one for sheep and one for cattle. Downloaded parameter sets, post simulation, can also now be saved and re-loaded for a later run.
2. Addition of automatically generated climatology charts for a location when new weather data is uploaded, and which can then be saved by the user. This also incorporates the prediction of snow depth at DOY1, which is automatically used to parameterise that value in the model.
3. Ability to turn off Soil Fertility dynamics for long-run simulations.
4. Inclusion of a second biomass based grazing residual. The new level 'Grazing Residual Target' works as the primary target under conditions of high grassland growth to determine the rotation between grazing areas.
5. Inclusion of simulated wool/fibre price variability in output sheets to enable post-simulation analysis.
6. Inclusion of a tool to explore relationships between key grassland canopy parameters and predicted fractional ground cover and grassland height, with ability to save and apply parameter sets.
7. Addition of diagnostic charts for understanding stocking rate, use of warm shed/pens and land management units/grazing areas, and changes in LAI and the soil fertility index.
8. Inclusion of dynamic mortality rate calculation across livestock classes and age cohorts which increases mortality rates from a basal rate when empty bodyweight falls below a critical low body weight.
9. Expansion of capacity for defining depreciable assets, including their description (up to 10 can now be included).
10. Simplification of layout for choosing Animal/Livestock type on the Livestock input sheet.

V1.07 (February 2020)

1. Extension of number of grazing areas (up to 30 grazing areas can now be included).
2. Inclusion of warm shed/pen feeding during periods of destocking or holding animals overnight, with capability to modify within shed/pen climate (temperature, wind, rainfall).
3. Inclusion of alternative grazing management options (Time based and Biomass based grazing rules).
4. Inclusion of alternative selling rules for young animals (<12mths of age) – may be separated from adult selling DOY to be based on a Target Sale Weight or DOY to be sold, whichever comes first.
5. Correction of potential errors in calculating selective grazing, body condition, conception and reproduction rates under well fed scenarios.
6. Inclusion of functions allowing for Triplets for sheep/goat enterprises (meat type only).
7. Inclusion of methane (CH_4) emissions from manure and nitrous oxide (N_2O) emissions from urine & manure, and combined with existing enteric methane emissions to present total livestock GHG emissions based on GWP_{100} CO_2e.

8. Inclusion of a grassland growth calibration option to derive best-fit alpha and gamma growth parameters from pre-loaded field data. Includes the capacity to run the model between specified years.
9. Inclusion of a seasonality index that accelerates spring growth rates (subject to predominant species type and legume content) to capture the effects of rapid leaf extension rates between the spring equinox and the switch from vegetative to reproductive physiological states.
10. Inclusion of Critical Residual Biomass as a selectable decision variable under Full Stochastic Simulations.
11. Addition of a series of charts under Stochastic Simulations that present key outputs for the final year of the simulation horizon.

V1.06 (February 2019)

1. Inclusion of simulation data and parameter export capability (post simulation).
2. Adjustment to wind erosion calculations and soil fertility/soil depth effects on grassland growth sub-models
3. Addition of extra diagnostic and data outputs and charts.
4. Ability to turn off grassland composition dynamics (i.e. maintain a constant botanical composition).

V1.05 (April 2018)

1. Modification of wind and total soil erosion. Wind erosion is now based on a process-based soil erosion model with diurnal wind speed variation and linked to soil moisture, fractional ground cover, canopy height and impact of a definable soil type on wind erosion susceptibility. Total soil erosion, including that due to wind and water (runoff) is now recorded and displayed separately.

V1.02 (January 2017)

1. Modification of DMD pools for grassland herbage mathematically allocated based on a nominated mean monthly digestibility of desirable and undesirable components (function DMDpoolProp.m).
2. K_m (efficiency of energy use) modified for un-weaned animals to allow for proportion of non-milk based diet.
3. Modification of reproductive rate to functions in 2012 Tech note.
4. Relative condition of the breeding animals modified to be net of any conceptus. Relative condition also applied in supplementary feeding rules.
5. Decision rule for lamb shearing – shorn or not shorn at first wool harvesting day (need to consider time between lambing date and wool harvesting/shearing date.
6. Cattle/yak parameters and growth modules, management calendar and grazing calendar introduced.

V1.01 (9th January 2017)

1. Working version of Sheep module with a series of review and diagnostic charts.
2. Inclusion of non-farm and subsidy income that supports household cash flow.
3. Price risk included with a normal distribution assumed around the stated mean expected price. Users are required to provide either the expected standard deviation of meat sale prices, or set to a value of zero, to simulate deterministic meat prices. For wool/hair prices, a mean price per kg clean can be inserted with an associated Co-efficient of Variation if price risk is to be considered in simulations.

Appendix B : Publications

Behrendt, K.; Brown, C.G.; Qiao, G.; Bao, Z. (2022). **Assessing the opportunity costs of Chinese herder compliance with a payment for environmental services scheme**. *Ecological Economics*. In press.

Behrendt, K; Kemp, DR; Udval, G; Jargalsaihan, G; Han, GD; Li ZG; Li P; Lkhagvaa, D (2021) **Modelling the long-term impact on herder incomes and environmental services in an uncertain world.** In *Proceedings of the XXIV International Grasslands / XI Rangelands Congress: Sustainable Use of Grassland and Rangeland Resources for Improved Livelihoods*, Nairobi, Kenya. 4 pages.

Brown, C.G.; Behrendt, K.; Li, P.; Qiao, G.; Bennett, J.; Bao, Z.; Addison, J.; Kemp, D.R.; Han, G.D.; Zhang, J. (2021). **Revising China's grassland policies: an interdisciplinary and ex-ante analysis**. *The Rangeland Journal*. 42(6), 435-445. https://doi.org/10.1071/RJ20097

Behrendt, K.; Takahashi, T.; Kemp, D.R.; Han, G.D.; Li, Z.; Wang, Z.; Badgery, W.; Liu, H. (2020). **Modelling Chinese grassland systems to improve herder livelihoods and grassland sustainability**. *The Rangeland Journal*. 42(5), 329-338. https://doi.org/10.1071/RJ20053

Behrendt, K; Liu, H; Kemp, DR; Takahashi, T (2020) **Sustainability modelling of grassland systems**. In 'Sustainable Chinese Grasslands.' Monograph 210 (Ed. DR Kemp.) Chapter 6 pp. 97-124. (Australian Centre for International Agricultural Research: Canberra)

Liu, H; Behrendt, K; Wu J; Du W (2020) **Modelling the sustainability of Qinghai-Tibetan Plateau grasslands**. In 'Sustainable Chinese Grasslands.' Monograph 210 (Ed. DR Kemp.) Chapter 7 pp. 125-152. (Australian Centre for International Agricultural Research: Canberra)

Kemp, D; Han, G.D.; Li, P.; Wang, Z.; Zhao, M.; Bombosuren, U.; Jargalsaihan, G.; Zhang, Y.; Hou, X.; Addison, J., (2020). **Grassland Livestock Systems**. Chapter 3, In C. Brown (Ed) Common Grasslands in Asia: a comparative analysis of Chinese and Mongolian Grasslands. Edward Elgar Publishing, Cheltenham UK. pp. 48-77 (ISBN: 978 1 78897 404 2)

Behrendt, K.; Cacho, O.; Scott, J.M.; Jones, R. (2016). **Using seasonal stochastic dynamic programming to identify optimal management decisions that achieve maximum economic sustainable yields from grasslands under climate risk**. *Agricultural Systems,* 145 (June 2016), 13-23. doi: http://dx.doi.org/10.1016/j.agsy.2016.03.001

Behrendt, K. (2015) **The value of modelling botanical composition change in grasslands**, In: A.K. Roy (ed), *Proceedings of the 23nd International Grasslands Congress*, 20-24 November, New Delhi, 3 pages.

Behrendt, K.; Cacho, O.; Scott, J.M.; Jones, R. (2013). **Optimising pasture and grazing management decisions on the Cicerone Project farmlets over variable time horizons**. *Animal Production Science, 53*(8), 796-805. doi: http://dx.doi.org/10.1071/AN11174

Behrendt, K.; Scott, J.M.; Cacho, O.; Jones, R. (2013). **Simulating the impact of fertiliser strategies and prices on the economics of developing and managing the Cicerone Project farmlets under climatic uncertainty**. *Animal Production Science, 53*(8), 806-816. doi: http://dx.doi.org/10.1071/AN11173

Behrendt, K. (2013) **Optimising management to achieve sustainable economic yields from grasslands**, Invited Poster Paper, In: D. Michalk; G. Millar, W. Badgery and K. Broadfoot (eds), *Proceedings of the 22nd International Grasslands Congress*, 15-19 September, Sydney, pp 883-884.