14. The development of feed balances for livestock

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14.1 INTRODUCTION

It is predicted that the world's population will increase by 2.3 billion over the next 20 years, and that this will be accompanied by an increase in the demand for animal products, namely milk, meat and eggs. A structured approach to planning for this increase in demand will be necessary if demand is to be met cost-effectively, with minimal social disruption and with minimal environmental impact. Part of this process requires an assessment of the available feedstocks and the requirements of the current livestock population, and this can be achieved by developing a livestock feed balance. Having done this, it is then possible to identify limitations to current levels of production and estimate the feed requirements for increasing production. A livestock feed balance can be undertaken at a local, regional or national level depending on policy requirements and the degree of accuracy required.

At its simplest level, a feed balance is a comparison between the requirements of livestock at any given time (demand) and the amount of utilizable feed (supply), and therefore provides a "snapshot" of the current situation. However, a feed balance can also identify potential shortages in feed to meet increasing demand for food, and help identify types of feed materials that might be required where shortfalls are identified. Alternatively, where a feed balance identifies a surplus of feed, it can be used to estimate the additional livestock production that the surplus might support.

This approach may also be undertaken to develop balances for specific nutrients. For example, phosphorus (P) is an essential nutrient that is often deficient in livestock diets, leading to reduced productivity and fertility. A phosphorus balance for a particular area or country can help identify where or when deficiencies might occur, and identify where and how much additional P may be needed to meet livestock needs and productivity targets.

Feed balances are usually calculated on an annual basis and, given that many feed crops, such as cereal grains, have an annual production cycle with one harvest, this may be appropriate. However, there is no reason why a feed balance may not be performed over a shorter period, and indeed there may be advantages in doing so in certain circumstances. For example, if there are periods of the year when the amount of natural grassland available for grazing animals is low, it may be appropriate to prepare a feed balance for those periods in order to establish the maximum potential livestock carrying capacity of a particular region when feeds are in limited supply. However, because the production cycles of many livestock systems do not equate to one calendar year, it is necessary to make adjustments to the feed balance to take account of the length of a particular cycle. For example, the cycle for growing and fattening pigs from weaning to slaughter may be only about 20–24 weeks in intensive production systems, but this may be followed by a period when the fattening house is empty to allow for cleaning and general maintenance before the next feeding period begins. If a feed balance is being prepared on an annual basis, it will be necessary to include both the length of the production cycle and the non-productive periods in calculating annual feed requirements and livestock production.

14.2 METHODS

In order to produce a feed balance, two sets of data and a number of processes need to be completed, and these are described below.

14.2.1 Estimating feed supply

Estimates of feed supply should be based on local, regional or national inventories. There has been considerable progress in developing techniques to estimate feeds available, and in particular forages. The merits or limitations of these are not discussed here, but depending on the specifications of the inventory and the way in which the available forages are quantified, it may be necessary to make adjustments for the following:

- Seasonality of supply
- Feed losses

Seasonality of supply: For many livestock, the availability of feeds may be reasonably consistent throughout the year. This will apply particularly to feeds such as cereal grains and conserved forages, where feeds can be stored without deteriorating in quality. However, in many regions a significant proportion of livestock, particularly ruminants, are kept under extensive farming systems, where the main or only feed may be native pasture. Seasonal changes in climate and growth stages of plants culminate in an annual cycle of forage production that peaks during the wet period and is severely limited during the dry period. As a result there may be periods of the year when grazing livestock are often unable to satisfy their nutritional requirements, resulting in lower growth rates and reproduction. It is important that where *annual* feed inventories are used, they are adjusted to take account of the peaks and troughs in supply relative to livestock numbers and their feed intake. Unless surplus feeds are conserved, e.g. forages conserved as silage or hay, then failure to do so may result in an over-prediction of available feed.

Feed losses: Despite the best husbandry and feed management practices, losses do occur; these are usually associated with harvesting and storage and in some circumstances these may be considerable. Some losses are inevitable, for example those associated with conserving forages (as silage or hay), where 30 percent or more of the dry matter may be lost as a result of field, storage and feeding out losses. Poor storage conditions for cereal grains, nuts and other crops can result in losses due to pest infestations and fungal contamination. Not only do they result in direct dry matter loss, but many are associated with the transfer of disease or production of toxins. Again, failure to adjust a feed inventory for these losses may lead to an overestimate of feed available.

In addition to forages, livestock are fed a wide variety of feeds. These may include cereal grains and co-products of cereal processing, oilseeds and oilseed meals derived from them, co-products of brewing and distilling, legume seeds, feeds derived from the manufacture of human food and animal products such as fish meal and processed animal proteins; collectively these are often termed “concentrates”. In addition, tubers or root crops such as cassava, and co-products derived from processing such as sugar beet pulp, are frequently important feeds. Information on the quantities of these used in animal feeds may be obtained from a number of sources including import statistics, production records from compound feed manufacturers and feed merchants.

As with forages, some losses are inevitable as a result of transport, manufacture and storage, and it is important to include an estimate of these in any feed balance calculation.

14.2.2 Quantification of herd /flock numbers and production traits

In order to estimate the demand for feed, an estimate of the number of livestock in a region or country is needed. Where regional or national statistics are available, these should be used. However, in some situations reliable data may not be available, in which case best estimates should be obtained based on local knowledge of livestock production systems.

Many feed and nutrient balances are based on census data, which provide an indication of livestock numbers at a given time. However, livestock numbers within a region might fluctuate considerably during the course of the year and, as a result, the use of data derived at one particular point in time may be misleading when applied to a full year. Where this is the case, adjustments in estimates of livestock numbers must be made, again based on local knowledge.

In addition to data on livestock numbers, some estimate of productivity is required so that the amount of feed required to provide energy demands for maintenance, pregnancy and production can be calculated. For growing and fattening cattle, sheep, goats, pigs and meat poultry (e.g. broilers, ducks) this will require estimates of daily liveweight gain. In addition, data on the output of livestock products (eggs, milk and fibre, or wool) are necessary, while for reproductive (breeding) animals data on numbers of offspring are also required. In summary, production data are required to show:

- Productive life of mature animals;
- Numbers of animals at the beginning and end of the feed balance period (usually the beginning and end of the year;
- Herd or flock production measured as:
  - calving/lambing/kidding/farrowing frequency
  - lactation length
  - milk production
  - liveweight gain
  - output of animal products (milk, meat, eggs, wool);
- Adjustments necessary to account for climatic extremes or physical activity.

For most feed balances, it is sufficient to provide estimates of liveweight gain and product production in terms of their weight. Where data are available to show that milk composition varies significantly from the breed average, then information on the composition of milk, particularly the fat and protein contents, should be used, because energy requirements vary for milk of different composition. If detailed nutrient balances are being undertaken, for example to establish a nitrogen balance, then data on the composition of animal products and liveweight gain will be necessary. In most cases, standard values for the composition of gain and livestock products will suffice.

14.4.3 Estimating feed requirements

Feed materials vary significantly in their concentration of nutrients and the contribution they make to meet the requirements of livestock. Energy is usually the first limiting component in livestock diets, and for this reason feed balances are normally calculated in terms of the energy required by livestock and the energy supplied by feeds. Therefore the next step is to estimate the energy needed by the livestock identified in in paragraph 14.4.2.

For each class of livestock, it is necessary to calculate the energy requirements for:

- maintenance;
- pregnancy;
- production (e.g. milk yield, liveweight gain, number of eggs produced); and
- in some situations, it may also be necessary to make adjustments for exercise and for extremes of climate (heat or cold), and for exercise where this is significant.

There is no one internationally accepted unit of energy, and different energy systems have been developed for different livestock groups. For ruminants, metabolizable energy (ME) is widely used as the measure of feed energy, while net energy (NE) values (expressed as either MJ or Mcal) are used in Denmark, France, Germany, Ireland, Netherlands, North and South America, and Switzerland. In principle, there is no difference between ME and NE systems; both accept that the overall energy requirement is the sum of their energy needed for maintenance, production (milk and liveweight gain) and foetal growth. However, they differ in how energetic efficiencies are embodied within the calculation. In the ME system, energetic efficiencies are used for ration formulation and the prediction of animal performance, while in the NE system energetic efficiencies are included as part of the energy evaluation of feeds.

For pigs and poultry, digestible energy (DE), ME and NE systems have all been proposed and are used in different countries. There have been long lasting debates as to the merits of each system, but in practice differences between systems in estimating total energy requirements for livestock are relatively small.

It is not the purpose of this chapter to review these various systems or to pass judgement on their relative merits. What is important is that the system chosen is one which includes both estimates of requirements for the livestock production in the region/country concerned, and also provides tables of feed composition that are appropriate for the feeds that are available in the region or country in question. It is also important that the system chosen is one that the user is most familiar with and feels competent in working with.

Systems providing both the nutrient requirements of livestock and the composition of feeds have been published by a number of national authorities, some of which are given at the end of this chapter. In addition, a number of breed companies provide nutrient requirements for livestock for particular strains or breeds.

Using the data on livestock numbers, together with information on reproduction rates and productivity, e.g. eggs produced, numbers of pigs sold or the amount of milk produced, the energy requirements can be calculated. This can be done on a daily basis and scaled up to provide an annual estimate. Alternatively, where production data are available for a region or country, it is possible to calculate energy requirements on an annual basis. It can be done for an individual flock or herd, or on a regional or national basis depending on the scale of the feed balance, the need for precision and the data available.

Reference has been made to the publications that provide energy requirements of livestock and it is strongly recommended that these be used. However, where possible, in producing detailed feed balances, the following can be taken as indicative values for planning purposes:

Pigs

Energy required for growth at different live weights[1]:	25 kg	22 MJ ME/day
	60 kg	34 MJ ME/day
	90 kg	40 MJ ME/day
Energy required for pregnancy:		3,280 MJ ME per sow (total)
Energy required for lactation:		2,565 total[2] per litter (total)

Poultry

Laying hens: 52 weeks of lay, 340 eggs:	430 MJ ME/bird
0–17 weeks (pre-laying)	72 MJ ME/bird
Meat chickens (broilers) to 6 weeks (LW ♀2.3 kg, ♂2.7kg):	54 MJ ME/bird

Ruminants

		Sheep	**Goats**	**Cattle**
	Liveweight LW (kg)		*MJ ME/kg LW/year*	
Energy required for maintenance	30	66	77	
	40	65	71	
	50	58	68	
	60	55	65	
	70		63	
	100			63
	200			51
	300			45
	400			41
	500			39

cont.

Notes:

[1] Derived from NRC (1998), Nutrient Requirements of Swine.

[2] Assumes a weaning age of 40 days.

Ruminants (cont.d)

		Sheep	Goats	Cattle
			MJ ME/kg LW gain/day	
Energy required for gain	< 3 months			
	> 3 months			
	< 6 months	26 – 34	26 – 36	
	> 6 months	41 – 49	37 – 49	
	< 1 year			19 – 26
	> 1 year			32 – 42
Energy required for pregnancy		1 480 MJ ME per ewe (total)[3]	2,150 MJ ME per dam (total)[4]	14 420 MJ ME per cow (total)[5]
Energy required for lactation		2 160 MJ ME total6	5.1 MJ ME/litre	5.3 MJ ME/litre[7]

[3] Assumes a 60 kg ewe carrying twins.

[4] Assumes dam carrying twins (total birth weight 7.9 kg).

[5] ME requirements for maintenance and pregnancy of a 600 kg housed, pregnant, non-lactating cow gaining 0.5 kg /day liveweight in addition to the foetus for a 40 kg calf.

[6] Assume a lactation of 3 months; milk requires 4.7 MJ/litre.

[7] For standard milk containing 4% fat and 3% protein.

14.2.4 Estimating energy supplied from available feeds

The previous steps make it possible to estimate the energy requirements of the herd or flock on a farm or on a regional or national basis. However, because most feed inventories describe the amount of feed available in terms of dry matter (DM[19]), it is necessary to convert this to the same energetic terms, i.e. MJ ME or NE in the case of ruminants, or ME or DE for pigs or poultry. Again, these should be expressed on a DM basis. Tables of feed composition and nutritive value are widely available, and these should be used to calculate the amount of energy provided by the feeds available.

However, the intake of feeds is not unlimited, and in order to obtain an accurate estimate of the contribution that feeds make in meeting the nutritional needs of livestock, it is necessary to include an adjustment to allow for variations in intake.

Despite the considerable research that has been undertaken to identify the factors that determine how much feed an animal will consume, experts do not agree on the mechanisms that control intake. It is clear, however, that a wide range of animal, feed and management characteristics influence intake, including:

- breed or strain of the animal/bird;
- age/weight;
- nutrient balance of the diet;
- accessibility to feed;
- health and welfare status;
- ambient temperature; and
- production level

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[19] This is the weight of feed after all moisture has been extracted.

In all livestock systems, the optimum feed intake will depend on the commercial goals of the enterprise within the constraints of the maximum potential intake of the animal or bird.

Where there is good access to feed, and health and welfare are optimum, then pigs and poultry would be expected to consume about 4–4.5 percent DM of their body weight per day as young stock, reducing to 3 percent of body weight in mature animals.

For ruminants, maximum DM intake is also likely to be 4 percent of body weight in young animals, declining to 2–2.5 percent in mature animals. However, where forages are the main or only feed, *voluntary* intake will be significantly influenced by the digestibility of the feed. Low digestibility feeds take longer to progress through the digestive tract, and as a result low digestibility is reflected in lower intakes.

In order to complete a feed balance, it is necessary to have an estimate of feed consumed, and the energy provided by it. However, predicting the intake of forages by ruminants has proved to be particularly challenging. A number of theories and equations have been developed to predict intake, many of them based on the digestibility of the forage, the amount of any supplementary feed, e.g. concentrate feeds, and the level of production. While they may be appropriate in many situations, an alternative approach for a feed balance is to use a form of reverse-balance calculation. Through this approach, the energy required for a given level of production – growth rate, milk yield, calves born etc. – is calculated. This is then divided by the energy concentration of the forage, after any energy provided by supplementary feeds has been discounted. This is illustrated below for a lactating dairy cow:

- Energy required for maintenance and production = 190 MJ ME/day
- ME provided by compound feed 1.8 kg DM at 12.5 MJ/kg DM = 22.5 MJ ME/day
- Energy from forages = 190 – 22.5 = 167.5 MJ/day
- ME content of forage = 10.5 MJ ME/kg DM
- Forage DM intake = 167.5/10.5 = 15.9 kg DM/day

In this example, dry matter intake is predicted as 15.9 kg/day but as discussed above it is necessary to allow for losses, and the estimate of the amount of feed required to sustain this level of production would need to be increased to adjust for these.

This approach can be used to calculate intakes on a daily basis for an individual animal, as illustrated above, but it can also be done for a herd of animals and on a monthly or annual basis. The choice will depend on the quality of the data available and the degree of precision required, although it should be noted that an annual estimate could lead to misleading conclusions where there is large seasonal variation in the amount of forage available. This approach can equally be used to make estimates of forage consumed on a regional or national basis, where data on the total output of milk or meat are available and the numbers of offspring produced are known. This approach is particularly appropriate for uniform categories of livestock such as lactating dairy cows or milking goats.

14.2.5 Reconciliation

Having established quantities of feed materials available and feed required by livestock, a surplus or deficit can be calculated. A surplus may suggest the potential for further livestock production, although it is important to establish when and where the surplus occurs. A surplus of forages during a brief period of the year or in an area not suitable to livestock production may not be fully utilizable unless livestock can be temporarily moved to the area. Alternatively, it may be possible to conserve the forage as silage or hay and used to supplement grassland when growth is low. In the case of a deficit, this can be rectified by increasing crop production or improving the efficiency of conservation of surplus forages by the purchase of feeds or a reduction in numbers of animals.

Feed deficits may be covered by feed imports. However, feed importation is not without environmental consequences. Although increased imports can sustain more animals, the increased numbers of animals may also increase grazing pressures on pastures and rangelands. Increased feed import also results in increased animal waste material and associated nutrients that must be appropriately managed.

As in the case of India, computed feed balances may indicate growing feed deficits despite counter evidence that livestock productivities have increased (see Chapter 9). Such discrepencies may point to increased reliance on feed resources that are important but overlooked or underestimated in feed inventories. Examples might include crop residues, industrial by-products, roadside vegetation, fallen tree leaves, seedpods that have fallen or been shaken down from trees, cut tree branches and other poorly quantified, but increasingly important feed resources in feed deficit situations arising from high livestock densities, intensive land uses, drought or severe winter weather.

Although a feed balance can be assessed at a national level, greater accuracy will be achieved if it is done at local or regional levels and the results consolidated. Because of the different feeds for ruminant and non-ruminant livestock, it is recommended that reconciliations are done separately for each species before producing a national feed balance.

14.3 REFERENCES

The following is a list of a number of national publications providing data on nutrient requirements and feed composition for livestock. In addition, livestock breeding companies frequently publish tables on nutrient requirements for specific breeds and strains of livestock.

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NRC. 2001. *Nutrient requirements of dairy cattle* (7th Revised edition). National Research Council. National Academy Press: Washington, DC, USA.

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15. The use of ecosystem simulation modelling to assess feed availabilities for large herbivores in heterogeneous landscapes

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15.1 INTRODUCTION

Arguably, the problem of assessing feed availability for livestock on spatially extensive grasslands and rangelands is essentially the same as assessing sustainable carrying capacity for large herbivores in heterogeneous landscapes. The primary objective of both is the same, to determine how many animals can be sustained by accessible forage and water. This in turn determines the amount of secondary production the livestock can provide to humans. Ecosystem modelling has been used to assess carrying capacities and it could likewise be used to assess feed availabilities.

There are many definitions of carrying capacity, but one would be that at carrying capacity, herbivores should not diminish the capacity of soils, vegetation and fauna to function together as an ecosystem. So defined, carrying capacity appears to be a straightforward concept. However, the task of defining what carrying capacity is exactly, and agreeing upon a method for calculating its value, is not easy. Definitions vary with management objectives, for example managing for maximum productivity, natural processes, or multiple and often conflicting uses of rangelands. More fundamental challenges arise due to the difficulty of calculating forage availability in temporally variable and spatially heterogeneous environments. Although remote-sensing data and GIS have enabled assessments of total vegetation productivity across space and time, additional complications arise concerning the consequences of that productivity for herbivores. Furthermore, herbivores affect numerous ecosystem processes through dynamic and interactive effects on plant growth, plant competition, nutrient cycling, organic matter decomposition, flows of water through plants and soil, competition or facilitation of other herbivores, and predation. These effects feed back onto the plants and herbivores at the ecosystem level of organization. Thus, an ecosystem approach is necessary to assess the effects of herbivory in the context of dynamic and spatially heterogenous landscapes.

There are substantial challenges in assessing feed availability on spatially extensive grasslands and rangelands. It is difficult to estimate feed availability simply by summing up total plant biomass, much less total green plant matter or even net aboveground primary production. The first challenge is temporal variability. Biomass availability fluctuates seasonally due to precipitation and snow cover. As a result, herbivores may be highly limited by the durations of low biomass availability. Forage quality also varies seasonally. Although green plants may constitute good forage, the same plants may provide little nutrition or be inedible when senescent. Second, forage quality varies among species. Some species are chemically or physically defended, or are avoided by herbivores for other reasons. Third, the fraction of total plant biomass or primary production that is accessible or usable by herbivores varies spatially. Plant biomass may be unavailable due to lack of nearby drinking water, snow cover, inaccessible topography, competition with wildlife and barriers such as fencing. As a result of these temporal and spatial constraints on forage availabilty, herbivore densities are often considerably lower than would be predicted on the basis of total plant biomass. In northern Kenya, for example, less than 10 percent of forage was consumed by pastoral livestock, yet forage was still a limiting factor to livestock densities (Coughenour *et al.,* 1985).

Herbivore populations are often limited by the amount of forage that is available on a limited portion of the landscape during dry seasons and winters. In many pastoral grazing systems, there are “dry season grazing reserves”. These are often areas that are less desirable to use during the growing season for some reason, such as overly warm temperatures at lower elevations, long distances to water or difficult topography. In northern Kenya, for example, livestock populations were limited to forage in locations that were little used during wet seasons (Swift *et al.,* 1996), which is why a small fraction of the forage in the whole system was consumed and why the herbivore population was smaller than might be expected given the apparent abundance of forage during the wet season (Coughenour *et al.,* 1985; Ellis and Swift, 1988). Limiting areas of this sort have been termed “key resource areas” (KRAs) (Ilius and O’Conner, 1999, 2000).

Ecosystem modelling is a powerful approach to assessing herbivores in ecosystems, both with respect to their responses to forage and other resources as well as their effects on vegetation and other ecosystem components. Several features of this approach make this possible. First, such models represent processes and outcomes of those processes as related to flows of biomass, nutrients, water and energy among soils, decomposers, plants, herbivores and the atmosphere. These flows include those which determine forage production and forage utilization by herbivores. Second, such models are dynamic. They represent important variations in time, among seasons and among years, as driven by fluctuations in temporally varying driving variables, particularly weather. Variances between wet and dry seasons, and warm and cold seasons all affect forage availability to herbivores. The durations and frequencies of food shortages are critical determinants of net outcomes for herbivores. Third, it is possible for such models to represent spatial heterogeneity. The spatial distributions of forage and water determine their availabilities, inasmuch as the spatial distributions of herbivores in space and time must intersect with the spatial distributions of these two critical resources. Fourth, models can be used to assess ranges of possible outcomes for herbivores due to ranges of variation in weather and management. Instead of a single number for forage supply, a range of outcomes might be anticipated. Fifth, issues of sustainability can be addressed at the ecosystem level. This entails continued viability of the entire food production system, inclusive of ecosystem services and biodiversity.

The objective here is to illustrate the ecosystem modelling approach by describing the application of such a model to assess an ecosystem supporting a population of large herbivores in western North America. A brief case study of the application of the model to a free-ranging horse population in the Pryor Mountain Wild Horse Range (Coughenour, 1999) shows the potential of ecosystem modelling to assess feed availabilities in spatially extensive grasslands and rangelands characterized by temporal variability and spatial heterogeneity.

15.2 THE ECOSYSTEM MODEL

SAVANNA is a spatially explicit, process-oriented, multi-species model of grassland, shrubland, savanna and forested ecosystems. It was first developed to represent a spatially extensive pastoral ecosystem in northern Kenya (Coughenour, 1992). The model has since been applied to a wide variety of ecosystems (e.g. Boone *et al.,* 2002, 2004, 2005; Boone, 2005; Christensen *et al.,* 2003; Coughenour, 1999, 2002, 2005; Kiker, 1998; Leidloff *et. al.,* 2001; Ludwig *et al.,* 2001; Weisberg *et al.,* 2002, 2006). SAVANNA is an integrated modelling aproach, paying equal attention to animals, plants and their interactions (Weisberg *et al.,* 2003). The overall structure of the model is shown in Figure 15.1. Details and applications of the model can be found at www.nrel.colostate.edu/projects/savanna/.

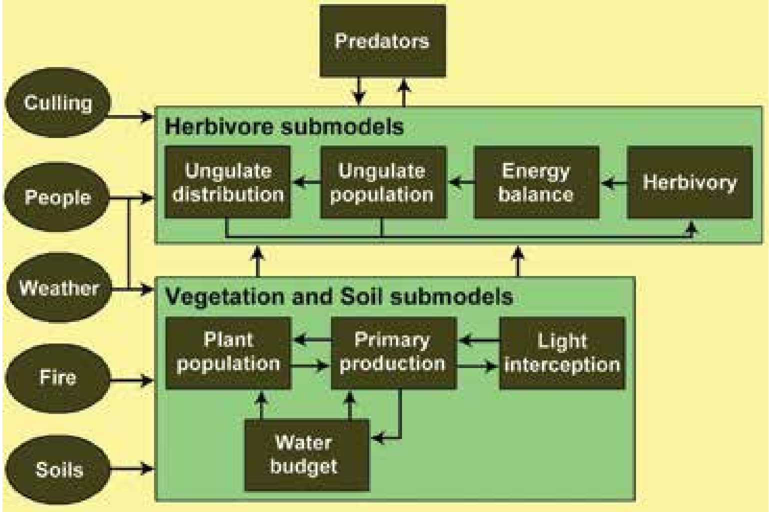
The spatial structure is a mosaic of grid-cells that covers landscapes or regional-scale ecosystems (Figure 15.2). Primary spatial inputs include GIS layers representing: 1) weather; 2) topography; 3) vegetation types and attributes; 4) herbaceous biomass; 5) woody cover and sizes; 6) soil types and attributes; 7) herbivore range maps, 8) distance to water; 8) fires. Animals, water, and fire can "move" across the landscape in the model. In order to carry out simulations in a reasonable time frame on workstation class computers, the total number of grid-cells is limited to between 10 000–100 000. Thus, when larger study areas are simulated, grid-cells must be larger. The model runs on a weekly time step, which is sufficient for capturing critical intra-annual and seasonal dynamics, but much less demanding than a daily time step. The model is normally run for 10–100 year time spans.

Monthly or weekly weather data from all stations in the study area are read into the model. The model computes precipitation and temperature maps from the point data as it is running, using elevation corrected spatial interpolation. A water balance model simulates soil moisture in three layers.

The site water balance submodel simulates soil moisture dynamics and use on each patch type on each grid cell. A soil map is used in conjunction with soil properties for each soil type to determine soil water holding capacities of each subarea. Water is routed to three soil layers using a simple "tipping bucket" approach that drains water in excess of field capacity to deeper layers. The water budget includes terms for precipitation, interception, runoff, runon, infiltration, deep drainage, bare soil evaporation and transpiration. Transpiration is an outcome of stomatal conductance, leaf area, humidity and radiation.

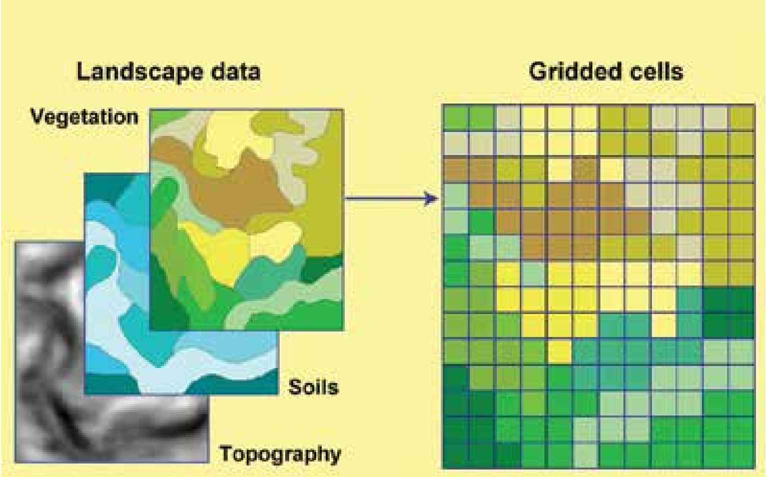
Snow water content is simulated by adding to the snow pack when there is precipitation with temperatures below freezing, and melting from the snow pack based on temperature and solar radiation. Snow depth is derived from snow water content. Increasing snow depths impedes herbivore forage intake rates. Because precipitation and temperature vary with location and elevation, snow depths also vary with location and elevation.

FIGURE 15.1
SAVANNA model structure



Source: R. Boone (graphics)

FIGURE 15.2
SAVANNA spatial structure



Source: R. Boone (graphics)

Normally 3–10 plant functional groups are simulated, where functional groups are usually defined in terms of life form (herb, shrub, tree), leaf longevity (deciduous, evergreen) and palatability. Plant biomass, functional group composition and woody cover are initialized on the basis of a vegetation map and a corresponding lookup table linking vegetation type to these attributes.

The net primary production (NPP) submodel simulates plant biomass flows and dynamics. Photosynthesis is modelled as a function of light, temperature, soil moisture, and plant nitrogen content. Respiration is separated into growth and maintenance components. Herbaceous NPP is allocated to leaves, stems and roots. Woody plants allocate NPP to leaves, fine branch, coarse branch, fine root and coarse root. Water demands are derived from the transpiration calculation. Nitrogen (N) demands are calculated based on the concentration of inorganic soil N. Root water and N uptakes to supply demands are allocated among soil layers in proportion to the products of available resources and root biomass in each layer. Predictions of plant biomass dynamics and primary production have compared favorably with available data in every application of SAVANNA. In most cases, available data at least include peak biomass over 3–5 years (e.g. Coughenour, 2005). Ideally, data for intraseasonal dynamics of live and dead biomass are used (e.g. Coughenour, 1999).

The woody plant population submodel simulates plant establishment, size and mortality in six age classes of aboveground stems. The sizes of stems in each age class are determined by growth histories, including exposure to fire and herbivory. Allocation of NPP in woody plants is tied to plant size through allometric relationships. The model represents woody plant morphometrics (dimensions and biomass) for six size classes of plants. These include dimensions for crown diameter, stem diameter, height and rooting zone area or the root biomass density per square meter of soil. Biomass values are specified for leaves, fine branches, coarse branches, coarse roots and fine roots for each of the size classes.

A decomposition and N-cycling submodel based on CENTURY[20] (Parton *et al.,* 1987, 1998), simulates litter breakdown and the formation and turnover of soil organic matter (SOM). Decomposition and mineralization rates are affected by temperature and soil moisture. The CENTURY decomposition model is quite general, and has been validated in many different environments globally. Soil carbon and nitrogen values are initialized by soil types on the input soil map.

The herbivore models simulate multiple animal species or functional groups. Each species or group is modelled individually, with separate parameters describing body size, energy requirements, foraging, demography, and so on. Herbivore forage intake is predicted as a function of animal body size, forage biomass (the functional response), and forage quality (due to decreased rate of passage in ruminants at low quality). Body size and digestive physiology effects on forage intake rate and forage quality are explicitly included. A diet selection submodel distributes herbivory among plant types and tissues using dietary preference weights.

The energy balance of the animal is a simulated outcome of energy intake and expenditure. An animal condition index is derived from resultant body weight gains and losses. Energy intake depends on forage biomass intake and forage energy content. Energy requirements can be expressed in terms of the digestible energy (DE), metabolizable energy (ME) or net energy (NE). The fraction of the gross energy content of forage that is undigestible is excreted as faeces. The DE fraction is the energy that is actually digested. Of the

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[20] The CENTURY model is a general model of plant-soil nutrient cycling which is being used to simulate carbon and nutrient dynamics for different types of ecosystems including grasslands, agricultural lands, forests and savannas.

amount digested, some is lost to urine and, in ruminants, to fermentation gases (methane) produced by rumen microbes. The energy left after these losses is the ME, which is used for maintenance, weight gain, gestation and lactation. Additional costs of walking and other activities can also be considered.

Herbivores are dynamically distributed in space using a dynamic habitat suitability index (HSI) model that dynamically distributes animals in proportion to the distribution of HSI, which is in turn computed from the potential rate of energy intake, green forage biomass, topography, woody cover and distance to water. The HSI formulation can be heuristically based upon known habitat preferences and logistic regression. Recently, Mahalanobis distance weighting[21] has been used (de Knegt *et al.,* 2010). Seasonal migrations are modelled by designating the seasonal ranges and making movements among ranges dependent on relative habitat conditions.

15.3 CASE STUDY

15.3.1 Study area

The Pryor Mountain Wild Horse Range (PMWHR) is located on the border between Montana and Wyoming, east of Yellowstone National Park. The PMWHR landscape is topographically diverse, with elevations ranging from 1 200 to 2 400 m. As a result of this elevation gradient, climatic conditions vary markedly with respect to temperature, precipitation and snow conditions. A complex and active geologic history has created a high diversity of geological substrates, including limestones, sandstones, shales, siltstones and granites. The vegetation of the PMWHR is diverse (Figure 15.3), primarily due to the large elevation and associated climatic gradient, but also due to the wide variety of soils and substrates and patterns of water redistribution on the landscape. Desert shrubland occurs at the lowest elevations (<1 200 m), sagebrush steppe occurs at 1 200–1 600 m, juniper/mountain mahogany shrublands and woodlands occur on very shallow soils at 1 100–1 550 m elevations, and coniferous forests occur at higher elevations above 1 600 m. An early census taken in 1970 prior to any removals totaled 270 horses. Numbers were reduced to the 100–120 range in the 1970s–80s through to the present. The range is shared with bighorn sheep, and mule deer and horse competition for forage with the bighorn sheep has been a concern.

15.3.2 Model implementation

The model was parameterized and input data sets were developed for the study site. The objective was to use the model to simulate historic and current scenarios of vegetation and herbivore management. The model would be used to estimate herbivory effects on vegetation and soils, and herbivore population responses to alternative management policies.

Six functional groups of plants were simulated; grasses, forbs, shrubs, mountain mahogany (*Cercocarpus*), juniper and coniferous tree. These groups were chosen to meet the objectives of this modelling analysis without making the model overly complex.

Three horse herds were modelled and limited to observed seasonal ranges. Seasonal

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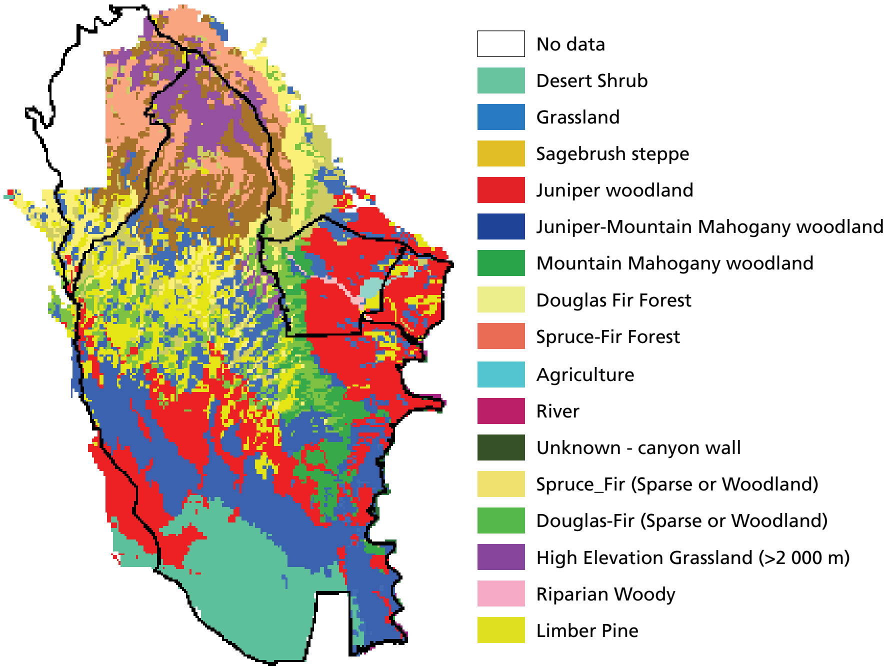
[21] Mahalanobis distance weighting is a procedure that measures the relative suitability of a habitat with respect to the known preferences of a species for multiple habitat variables.

FIGURE 15.3
Vegetation heterogeneity on the PMWHR



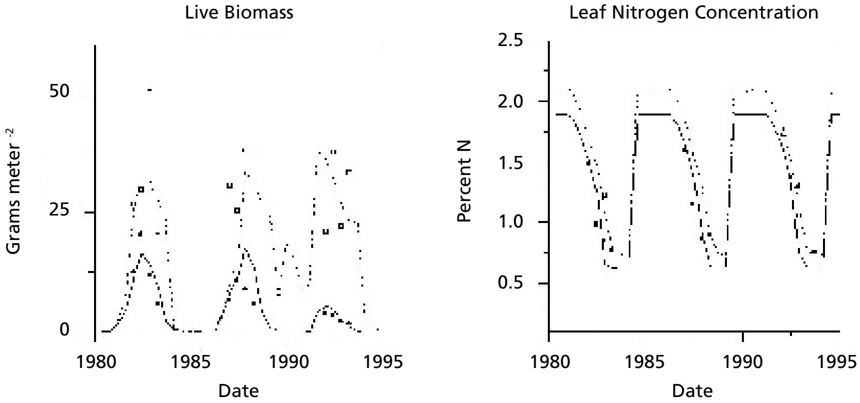
movements were modelled as dynamic responses to changing forage and snow conditions, with a seasonal avoidance of low elevations in summer. Habitat suitability increased with forage biomass and forage energy intake rate. Horses were assumed to prefer areas with moderate topography. Water is a major determinant of horse distributions during the spring, summer and autumn, while snow is available to horses during winter, allowing horses to use virtually all of the horse range. The model was parameterized so that there was a high preference for water less than 1.5 km distant, declining with greater distances so that areas beyond 6 km of water were considered unuseable.

Bighorn sheep were kept within observed seasonal ranges and redistributed within the ranges in relation to forage biomass, forage energy intake rate and topography (escape terrain). Mule deer were present during the winter and had access to the entire landscape, but avoided steep slopes.

The capability of the model to predict herbaceous shoot biomass and leaf nitrogen dynamics was tested through comparisons of simulated results with field data for plant biomass dynamics (Detling *et al.,* 1996). Optimally, a dynamic model such as this one, which aims to simulate seasonal dynamics, is tested against data which show these dynamics. Furthermore, to assess total productivity and grazing impacts on vegetation, grazing exclosures need to be employed. Data were taken inside and outside of each exclosure. Live and dead shoots of grasses and forbs were measured, along with leaf N concentrations. An example comparison of simulated and observed data at one exclosure is shown in Figure 15.4.

FIGURE 15.4

Comparison of simulated (lines) and observed (points) data at one exclosure site



Note:
Solid lines and filled points – grasses.
Dashed lines and open points – forbs.

15.3.3 Example results

The main purpose here is illustrate the types of outputs that are provided by this type of model. It is necessary to examine graphical outputs that show both temporal dynamics and spatial heterogeneity to reveal the capability to address the major challenges of assessing feed availabilty in spatially extensive grasslands and rangelands.

With respect to temporal variations, Figure 15.5 shows the temporal dynamics of herbaceous biomass over three decades. The important features to note are the magnitudes of the inter-seasonal and inter-annual fluctuations, which are significant determinants of feed availability. Figure 15.6 shows the temporal responses of forage intake rate to feed availability, as affected by biomass, snow cover and animal locations. Figure 15.7 illustrates the resultant dynamics of animal condition in response to fluctuations in forage availability and intake rates.

With respect to spatial heterogeneity, Figure 15.8 exemplifies model predictions of the distribution of potential forage biomass across the landscape, in terms of net annual primary production (NAPP). Figure 15.9 shows the predicted spatial distributions of horses year-long. Figure 15.10 then shows the combined results of animal distributions and plant growth distributions for percent offtake.

15.4 CONCLUSIONS

The application of a spatially explicit ecosystem model to a landscape in North America inhabited by free-ranging herbivores illustrates both the challenges of assessing feed availabilities in spatially extensive grasslands and rangelands, and the potential of the ecosystem modelling approach to address these challenges. The model has been applied to similar situations elsewhere.

FIGURE 15.5
Temporal variations in grass and forb biomass

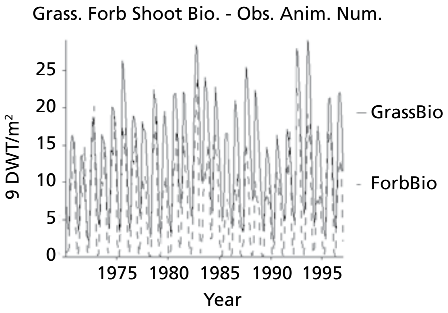


FIGURE 15.6
Temporal variations in forage intake rate in response to fluctuations in feed availability

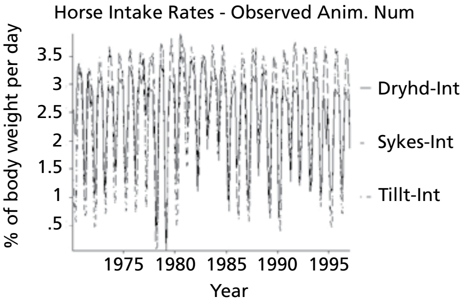


FIGURE 15.7
Responses of animal condition index to variations in feed intake

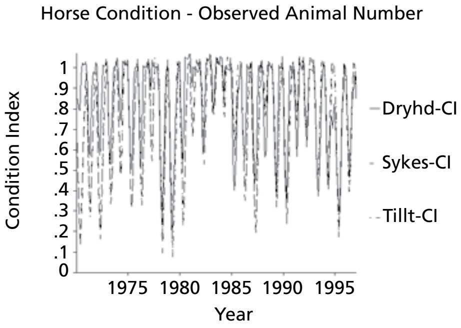
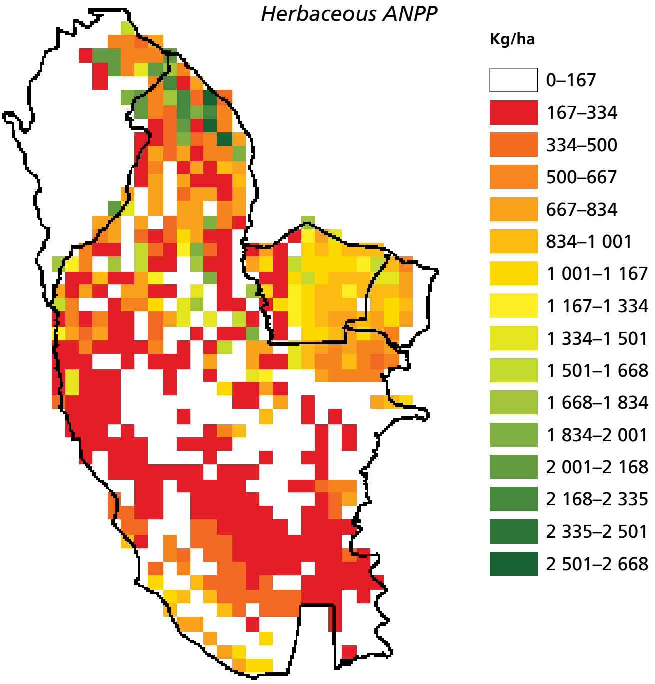


FIGURE 15.8
Spatial distribution of aboveground net primary production (ANPP)



Herbaceous ANPP

FIGURE 15.9
Spatial distribution of horse densities year-long

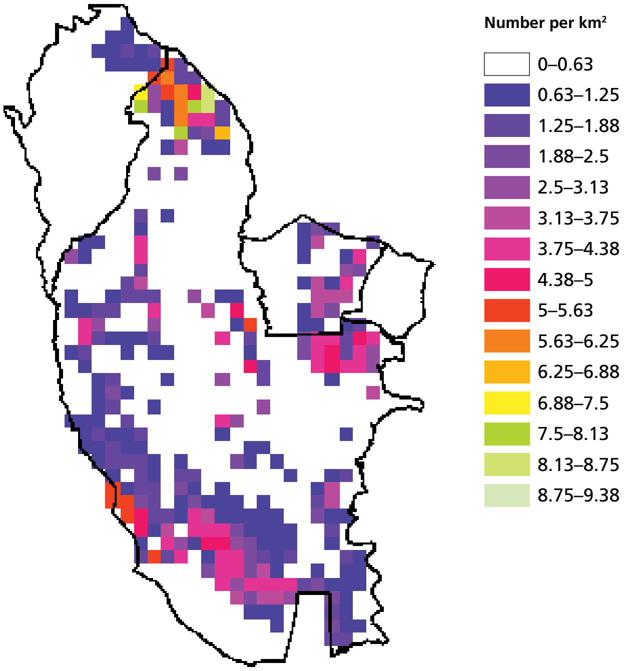
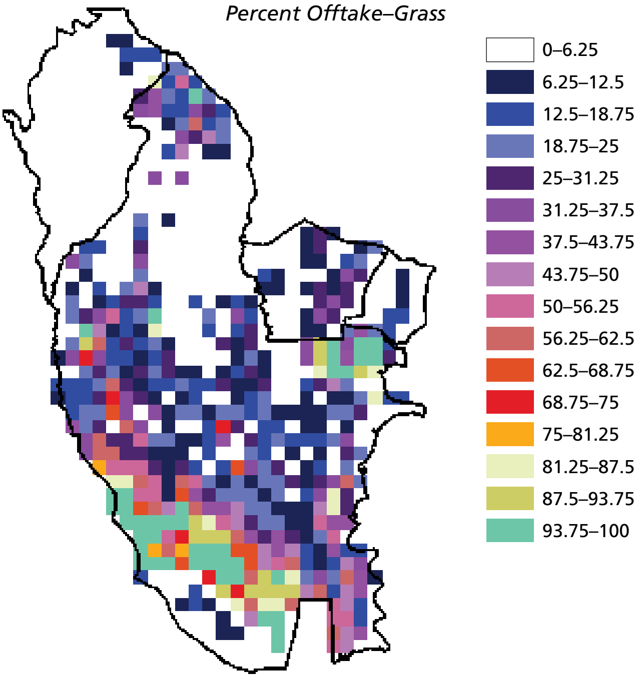


FIGURE 15.10

Spatial distribution of percent offtake of grass productivity, a net outcome of the spatial distributions of plant growth and horses



Feed availability was assessed, first of all, by predicting plant production and biomass dynamics based on weather, soil properties, and vegetation composition and cover. Plant growth was tightly linked with soil water balance, which is particularly important in water-limited grasslands and rangelands. Seasonal and inter-annual fluctuations in plant biomass quantity and quality were predicted as a result of corresponding variations in precipitation and temperature. Temporal variations included variations in live versus senescent biomass, and variations in tissue nitrogen and digestible energy contents. The spatial distributions of plant growth were outcomes of the spatial distributions of weather and soil properties. Precipitation and temperature maps generated from spatial interpolation, along with soil properties, were the principle driving variables for temporal and spatial variations in plant productivity.

The problem of there being multiple plant types with varied values for herbivores was addressed by simulating multiple plant functional groups. Herbaceous plants were distinguished from woody plants, which is of major significance in distinguishing feeds available to grazing versus browsing herbivores. Futhermore, leaf biomass of woody plants may have been out of reach of browsing herbivores due to height above the ground, which is simulated by virtue of woody plant sizes.

Availabilities were also predicted to be constrained by the overlaps of simulated animal distributions with simulated plant biomass distributions. Animal distributions were constrained by distance to water, topography and snow, and they were affected by animal selectivities for areas with greater forage quantity and quality. The juxtaposition of plant and animal distributions in time determined foraging opportunities, with subsequent impacts on forage intake rates.

The simulation of animal energy balance was central to predicting potential animal production responses to feed availability. In the context of this document, this has significant implications for assessments of the consequences of feed availability for livestock production. What the model accomplishes is essentially equivalent to a dynamic calculation of feed balance, the balance between animal nutritional intake versus requirements. Here, the feed balance was affected by spatial and temporal variations in feed availability, which in turn was affected by many environmental variables, including vegetation, topographic and snow cover variations.

The concept of key resource areas was addressed by simulating the temporal and spatial variations in forage quantity and quality just described. As dry seasons progress, or as winter conditions deteriorate, actual "forage" – as opposed to biomass – becomes increasingly limited in its spatial extent to areas with soil moisture reserves, areas that have not been grazed yet, and areas that are otherwise located in less desirable locations due to topography, distance from water or other factors. The spatial extents of these areas vary in the model inasmuch as the spatial extents of simulated resources (especially soil moisture) vary spatially and temporally.

Although the technological and data demands on the ecosystem modelling approach are currently daunting, ultimately it will become feasible to implement this approach quite readily. Data availability is increasing due to advances in remote-sensing and GIS capabilities. Computational limitations continue to be be lifted with hardware advances. What is most limiting is modelling expertise.

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