SECTION I

State of knowledge

1. Trends in demand for feed

In the developing countries, consumption of meat has been growing at over 5 percent annually in the last few decades and is expected to grow by 1.4 percent per year worldwide to 2030 (FAO, 2006a). In energetic terms, consumption of meat increased more than threefold that observed in developed countries from 1971 to 1995 (Delgado *et al.,* 1999). A major reason for the increase is that consumption has been rapidly growing in a number of large countries including Brazil, China and India (FAO, 2006a). Poultry production and consumption has been growing at more than 5 percent annually and is an increasing fraction of mean world production, from 15 to 30 percent over the last three decades. By 2050, 2.3 times as much poultry meat and between 1.4 and 1.8 times as much that of other livestock products will be consumed as in 2010 (FAO, 2006a; FAO, 2011). In India, the demand for poultry is expected to increase 844 percent by 2030, which translates to 8 865 400 tonnes of poultry products. This will require over 27 million tonnes of feed and an additional 24 million hectares of crop land unless the proportion of by-products and non-conventional resources in feed increases substantially and/or the contribution of backyard scavenging birds to poultry production increases (Chapter 7). Consumption of livestock products is closely related to per capita income. As incomes in many developing countries have grown rapidly over the last 20 years, consumption levels of meat and other animal products have also increased (Steinfeld *et al.,* 2006). Increases in income will encourage higher consumption per person, particularly in the developing world (FAO, 2011). As a result, total consumption in developing countries will eventually exceed consumption in the developed countries.

In Asia, human demands for animal source foods are beginning to outstrip production, with projections of two to threefold higher demand in 2050 in most countries (Devendra and Leng, 2011). These authors also point out that limited supplies of inexpensive grain feeds will drive more intensive use of forage, crop residues, agro-industrial by-products and non-conventional feed resources, and there will be an increased focus on making maximum use of crop residues and low quality roughages. They suggest that the two billion tonnes of straw the world produces could be converted into animal products with a feed conversion efficiency of about 10:1 to produce 200 million tonnes of live animals annually which could support four billion people.

In much of the developing world, mixed crop-livestock systems are prevalent. These are systems in which livestock are intimately tied to crop production through their use of crop residues, livestock recycling of nutrients and use of livestock for draft power (Herrero *et al.,* 2010). According to their analysis, mixed systems produce almost 50 percent of the world's cereals and most of the staples consumed by poor people, 41 percent of maize, 86 percent of rice, 66 percent of sorghum and 74 percent of millet. They also produce 75 percent of the milk and 60 percent of the meat, and employ many millions of people. Some crops such as maize, wheat, sorghum and millet are dual purpose – their grain provides food for humans and their residues are used as feed for livestock.

Livestock systems are intensifying. There is an increasing intensity of feed grain use, along with increased use of protein rich feeds and additives that enhance feed conversion. Meanwhile, traditional feed utilization is in decline (Steinfeld *et al.,* 2006). Historically, the use of grain to feed animals has primarily been a practice of developed countries. For example, 40 percent of cereals are used for livestock feed in the United States, while only 14 percent are used for feed in Africa. Additionally, while animal source food (ASF) consumption is very high, perhaps excessive, in the developed world, there is considerable room for increased incorporation of ASFs into diets in the developing world to improve nutrition (Speedy, 2003). There has also been a shift of world livestock production out of regions that use grain-intensive feeding systems into developing countries where grain is less important as a feed. However, it is quite likely that the opposite trend will occur – that continued growth of livestock production in developing countries will be associated with shifts to more intensified systems making greater use of cereals (FAO, 2006a). It has also been suggested that in developing countries, increased demand for food crops will compete with increasing demands for livestock feed, so substantially more feed grains will have to be imported (Delgado *et al.*, 1999). Due to increasing human populations in south Asia, intensive mixed systems will have to attain all their production from alternative feed sources apart from stovers, because stover feeding only meets animal maintenance requirements (Herrero *et al.,* 2009).

China has experienced a very large growth in demands for dairy products due to rises in income, changes in urban lifestyles and overall development of the dairy sector (Simpson, 2006). Milk consumption per capita tripled from 1985 to 2000, then doubled from 2000 to 2004. If China develops further, there will be an increasing shift to modern dairy farms, which will benefit from advances in genetic, breeding and dairy management worldwide. A pressing issue is the extent to which the dairy industry will be able to meet future demands. This leads to the question of whether China can provide sufficient feedstuffs for the growing dairy industry. A complex model-based assessment of these questions (Simpson, 2006) concluded that protein-based feedstuffs will increasingly have to be imported, while energy-based feedstuffs exist in abundance. Importantly, the assessment considered the fact that each country feeds its animals according to resource availabilities, tastes and preferences, and comparative advantages in production of feedstuffs (Simpson, 2010a). China will not, as many assume, move towards the large-scale feedlot systems typical in America, for example. A large fraction of national energy-based livestock feeds will be derived from crop residues (38 percent) and crop by-products including silage (21 percent). An even larger fraction of protein feedstuffs will be derived from crop residues (28 percent) and by-products (48 percent). By-products, non-conventional feeds and forages will continue to constitute a substantial portion of feedstuffs for dairy cows in much of China over the next decade, especially in the less populated areas. Consequently, considerable attention must be paid to assessing the stocks and flows of these feed sources.

Given the ongoing and expected future increases in animal source food consumption, there is increased controversy as to whether cereals and other foods that humans can eat could be fed to livestock (Speedy, 2003). While some argue that increased demand for animal source foods will increase demand for grains used for humans, livestock can consume crop products that otherwise would become waste or they can be raised on land that has no crop-based agricultural potential (Delgado *et al.,* 1999). Land availability and water will be key constraints to the production of alternative feeds for ruminants in the most intensive systems (Herrero *et al.,* 2009).

2. Assessing feed supplies in relation to increasing demands

The needs for developing national feed inventory or assessment systems vary among countries. In Switzerland, for example, feed inventories were developed out of strategic necessity during the World Wars to ensure continued food security (Chapter 8). Today, the need for continued food security still necessitates the acquisition of information that is necessary for coping with unplanned situations that could lead to food shortages, including droughts and disruptions in transport and shipping. Other uses have since arisen, including uses in calculations of national economic, biomass, nutrient and greenhouse gas fluxes.

Few countries in Asia have endeavoured to carry out quantitative or even qualitative assessments of feed availability, probably due to inadequate methodology and understanding of assessment approaches (Devendra and Leng, 2011). Assessments have been attempted for Peninsular Malaysia (Devendra, 1982), the Philippines (unpublished citation in Devendra and Leng, 2011), and oil palm areas in Southeast Asia (Devendra, 2009). Feed balances have been developed to assess availability and requirements in India and Pakistan (Mudgal and Pradhan, 1988; Raghavan, Krishna and Reddy, 1995; Ramachandra *et al.*, 2007) as well as Nepal (Shrestha and Pradhan, 1995).

Livestock feed shortages have clearly constrained productivity in India, as shown in numerous site-specific studies (Chapter 9; Ramachandra *et al.*, 2005; Raju *et al.*, 2002; Anandan *et al.*, 2005). However, the impacts of feed shortages at a national level have been poorly characterized due to the lack of national-scale feed assessments. A notable characteristic of Indian livestock is that almost its entire feed requirement is met from crop residues and by-products: grasses, weeds and tree leaves gathered from cultivated and uncultivated lands; and grazing on common lands and harvested fields (Dikshit and Birthal, 2010). Use of crop residues increased by 65 percent between 1980–81 and 2002–03 (Ramachandra *et al.,* 2005).

Livestock feed inventories in India, would be useful for policy-makers, government agencies, NGOs and development agencies. The information such inventories provides can be used in formulating and implementing meaningful livestock development activities and tackling natural calamities such as drought and floods (Chapter 9). Such information would also be useful for making informed decisions relevant to the nature and quantities of commodities, the feed resources that could be traded locally, potential areas for feed markets, and feed resources involved in imports and exports. Estimates of feed demand could help resolve the controversy regarding estimates of the fraction of food grain that is used for feed, which vary widely (Dikshit and Birthal, 2010). Estimates could also be used to determine the input-output relations for the livestock sector and to estimate greenhouse gas emissions associated with livestock production. Ramachandra *et al.* (2005) recommended a national feed balance approach that recognizes regional differences in livestock systems, along with a national networking system on crop and animal statistics, and the establishment of a Directorate of Animal Feed Resources Bureau to create the necessary databases and to plan and implement feed resource utilization at the national level.

Sources of livestock feeds have been identified and inventoried in Pakistan. Crop residues, cultivated fodder, grazing and concentrates contribute 57 percent, 18 percent, 19 percent and 6 percent respectively, to national livestock feed supplies (Habib, 2010). Mixed crop-livestock farming systems are widespread. After grain harvesting, crop by-products such as straws and stovers are stored and saved for year-round livestock feeding. Fodder is cultivated on a limited land area of 2.45 million hectares or 11.1 percent of the total cultivated area. Over the last two decades, fodder land has progressively decreased while fodder production has increased by up to 13 percent, apparently due to improved farmer practices (Habib, 2010). Grazing lands cover more than 20 million hectares in Pakistan, yet only contribute 19 percent of the biomass and 30 percent of the crude protein (Habib, 2010) to the total feed supply. The production potential of grazing lands has clearly declined, but the extent of the decline has been poorly quantified. Uncontrolled grazing and recurrent drought have considerably reduced their carrying capacity. Large influxes of sheep flocks from Afghanistan have placed further pressure on grazing lands. Community herd grazing at the village level, once a common practice in rural areas, has almost discontinued and farmers now graze individually. This has made it more difficult to implement rotational grazing/restricted grazing practices for protecting vulnerable rangelands. The century-old "nagha system" of restricted grazing, designed to protect common grazing lands from uncontrolled free grazing, no longer exists, or is practised to a very limited extent (Ghulam Habib, pers. comm.).

In the Africa Sahel, pastoralists graze their livestock in spatially extensive grazing systems characterized by large-scale seasonal movements among pastures as well as intra-seasonal grazing orbits in proximity to water sources (Chapter 10). Livestock forage production is limited by rainfall, which is highly variable. Pastoral livestock movements are responsive to variable distributions of forage in space and time. Periodic droughts are intrinsic to the system, leading to shortages of forage for livestock and food insecurity for pastoralists. The spatially extensive and time-varying nature of the forage resource, coupled with constraints on livestock movements created by water distributions, topography and infrastructure, necessitates an approach that is very different from the approach to assessments of livestock feed. The use of remote-sensing data, particularly of green vegetation biomass, has proved to be the only feasible approach. Thus, famine early warning systems utilize remotely-sensed greenness indices. The system described in Chapter 10 provides useful information for food aid organizations, pastoralists, governments and development agencies.

Similar situations exist in southern Africa, where a significant proportion of the human population is dependent on livestock for livelihoods and food, and where most of the livestock obtain their forage from rangelands (Chapter 11). The high spatial and temporal variability of forage production necessitates monitoring over broad spatial scales on a regular basis throughout the growing season.

An understanding of forage biomass availability across the landscape can assist Mongolian pastoralists make decisions about whether to move, buy or sell animals, and assess the level of risk for decision making (Chapter 12). However, extensive information about forage distributions over large remote areas is difficult, if not impossible to acquire. As much as 35 percent of Mongolia's livestock were lost during droughts and severe winters from 1999 to 2001. In response, the U.S. Agency for International Development (USAID) supported the development of a Livestock Early Warning System (LEWS) for the Gobi Region that provides near real-time spatial and temporal assessments of current and forecasted forage conditions. This information is provided to herders and to local and national government agencies to assist in drought management, disaster preparedness and agricultural policy-making.

The Tibetan Plateau is another example of spatially extensive pastoralism in remote and heterogeneous landscapes (Chapter 13). The human and livestock populations of the Tibetan Autonomous Region have both more than doubled over the last 40 years, resulting in increased demands on natural resources. Increased pressure, including livestock overgrazing and droughts, have resulted in grassland degradation and desertification, decreasing the available resource base and exacerbating the pressure. Thus, a livestock feed inventory would be useful in determining the availability of forage resources in relationship to demands. Such information would be relevant to food security policy and planning, as well as to the setting of sustainable stocking rates and environmental protection. Due to the expanse and remoteness of most of the pastoral grazing areas, and the challenges of working at a high altitude, low oxygen environment, ground-based field data on grassland productivity are very limited. A feed inventory for such a spatially extensive pastoral region must therefore employ remote-sensing data to the greatest extent possible.

A workshop held in 1985 in Nairobi brought together a number of scientists to assess feed resources for small-scale livestock holders in Africa (Katigele *et al.,* 1987). Although dated, it is instructive to observe the various approaches used to assess livestock feeds in developing countries at the time. In general, the assessments involved examinations of various types of feed resources such as natural grasslands (rangelands), improved pastures, cereals and root crops, and agricultural by-products. Typical total crop productivities and estimates of total cropped areas were reported based on a variety of government and Food and Agriculture Organization (FAO) statistics. However, little was done in the way of determining what was actually available to livestock. Similarly, typical values of plant production in rangelands were often presented, but quantitative inventories were not attempted, no doubt due to a lack of data across large and heterogeneous areas. Today, we have access to vastly improved databases, GIS, remote sensing and modelling capabilities. Yet, the potential of these information sources and technologies to develop national-scale feed assessments has barely been tapped.

3. A summary of case studies on national, regional and global feed assessments

3.1 SWITZERLAND

The Swiss feed balance

Switzerland has been carrying out regular feed inventories since 1933 with revisions to the methodology in 1980 and 2009 (Chapter 8). The Swiss approach is highly evolved, benefitting from experience, technical capabilities, and rich and well-organized sources of fundamental input data. A wide range of feed sources is considered, including both intensive crop-based and extensive grassland-based systems. Livestock considered include cattle, sheep, goats, pigs, poultry and horses.

Annual feed availability is calculated for a year from an inventory of domestic feed production, including crops and agricultural by-products. Availability is corrected for national feed imports and exports. Availability is expressed in terms of digestible or metabolizable energy and protein, using best available forage quality data.

As a check, animal demands for feed are calculated on the basis of livestock census data and animal energy and protein requirements. Differential requirements of breeding, fattening and milking animals are distinguished. Requirements are based on data from agricultural research stations and a well-established handbook (Agridea, 2011) for livestock growers.

Switzerland is fortunate in having excellent sources of data inputs for the inventory. The federal government regularly estimates crop production statistics at a national level. Food processing by-products are estimated from industry sources (milling, brewing) or by the government agricultural offices. Government production statistics are available for fodder maize and grassland forage production. Maize and grassland forage productivity from government statistics is corrected for altitude and meteorological conditions. Areal extents of seasonal grazing areas in the mountains are based upon infrequent (10–12 years) land-use mapping and GIS analyses.

Maize and grassland forage utilization is estimated to enable comparisons with forage availability. The two are presumed to be in balance over a multi-year period, with some having excesses and some having deficits. A forage deficit is covered by imports, or by drawing down standing stocks that have accumulated in years of excess. Utilization is based on typical dry matter intake rates of each livestock class and the duration of grazing.

3.2 INDIA

The Indian feed inventory

Several assessments have been carried out at regional level. Assessments have been based on land use data, crop production data and livestock census data (Anandan *et al.,* 2005;

Raju *et al.,* 2002). These data were obtained from the government Directorate of Economics and Statistics, and the Animal Husbandry Department. These researchers built on their experience to develop a database system with a user-friendly interface for accessing feed availability and requirements for the entire country (Angadi *et al.,* 2005).

An approach taken to assess national livestock feed supplies in India is described in Chapter 9. In this approach, crop-based feed availability is estimated from crop production data and green fodder availability is estimated from land classification data. Crop production and land utilization data (which include fodder land use types) are published annually. *Harvest indices* (the ratio of tonnes of utilizable crop by-product to tonnes of primary crop harvested) and *extraction ratios* (the fraction of primary crop harvested utilized for livestock feed) are applied to the crop production data to estimate feed availabilities. Harvest indices are used for crop residues and oil cakes, while extraction ratios are used for grains and bran/husks. Relatively crude estimates of green fodder production in various land types are used, along with estimates of percentages of land areas utilized for fodder production. These are approximations of mean values based on best available data. The production estimates are then applied to total land use areas, derived from land use maps and inventories.

Livestock feed requirements are estimated from livestock census data, which are published every five years. Livestock census data, broken down by species and age class, are converted to standard adult cattle units based on differences in body size. A basic estimate of dry matter requirements of 2 percent of body weight per day is then applied. Total dry matter requirements are compared with total feed availabilities to determine national feed balance.

Dikshit and Birthal (2010) calculated feed demand in India by scaling up from household level data. They argued that household level surveys are the only way to obtain reliable data on actual feed consumption. Scaling up was enabled by a sampling design that was intended to be as representative as possible across the wide range of heterogeneity of soils, topography, rainfall, irrigation, temperature, crops and livestock. The country was divided into 20 agro-ecological zones with further classification into 60 subzones based on variables such as soils, topography, rainfall, irrigation, temperature and crops. Furthermore, livestock were categorized by species, breed, age class and production status. Feed demands for each class of animal could then be combined with the distribution among classes to arrive at a more accurate estimate of aggregate demands. The scaling up was a multi-stage procedure, from households to villages, then from villages to districts, districts to regions, and regions to the nation. This accounted for the heterogeneity of villages in a district, and so on. These authors also compared feed demands with availability. They pointed out that the Ministry of Agriculture uses a general assumption that 5 percent of food grains are used for feed. They cited other literature with crop specific extraction rates (i.e. the fraction of total crop production utilized for feed), for example 9.5 percent of rice production and 41 percent of coarse cereal production. They projected future demands for feed in 2020 by first using "base year" feed consumption rates derived from their data, coupled with projected growth of livestock populations by types. They then revised the estimates to account for projected changes in demands for milk and meat. Based upon previous work, they predicted that future demands in milk would be met by increase in production per animal as well as numbers, while increased meat demands would be met primarily by increased animal numbers. However, irrespective of whether it is production per animal or numbers of animals, the energy requirements should remain the same unless feed conversion efficiency is somehow increased.

Mixed crop-livestock systems are very prevalent in much of the country, and there is great variety in the make-up and functioning of these households (Erenstein and Thorpe, 2010). The use of crops, crop by-products, forage, crop residues and other non-conventional feeds also varies markedly. It would be useful to understand this heterogeneity to more accurately assess livestock feed requirements. In the Indo-Gangetic Plains, uses of various types of livestock feed sources vary along an intensification gradient (Erenstein and Thorpe, 2010; Thorpe *et al.,* 2007), as determined by detailed village level surveys. Communities were randomly selected in a stratified cluster approach. Stratification was first applied to four sub-regions, then at the second level, three representative districts were selected, one from each of three main agro-ecological sub-zones. At the third level, six villages were randomly selected around a central point. This stratified approach is key to obtaining a representative sample, and for understanding how livelihoods and associated livestock feeding patterns vary in these systems.

3.3 PAKISTAN
The Pakistani feed inventory

The approach used in Pakistan is very similar to that used in India. In 2003, detailed calculations were carried out of feed availability and feed balance in different regions of the North West Frontier Province (now called Khyber Pakhtunkhwa) (Habib *et al*., 2003). Recently, a country level feed balance was carried out, including assessments in other provinces (Habib, 2010). Using crop conversion factors (like the harvest indices and extraction ratios used in India) found in the literature, and local data on crop productivities, quantities of crop residues and by-products derived from different crops were calculated approximately. Data on conversion factors for calculating crop by-product biomass need to be further developed and standardized.

Similarly, herbage from various categories of grazing lands was estimated using locally reported values for production and areas of grazing lands in ten different agro-ecological zones. However, the reported herbage yields from grazing lands in different ecological zones require updating and refinement, particularly because rangelands have degraded over the last 2–3 decades.

3.4 CHINA:
Present and projected livestock feed availabilities

Simpson, Cheng, and Miyazaki (1994) carried out a comprehensive assessment of agriculture in China in which they calculated present and projected livestock feedstuff availabilities. The calculations began with data from grain and oilseed crop production (total tonnes) and sown areas (hectares) from the China Agriculture Yearbook. Productivity per unit land area was calculated by dividing total production by sown area. Grains included wheat, rice, coarse (maize, sorghum etc.), while oilseeds included groundnut, rapeseed, sunflower and sesame. Other crop production statistics were also available including, for example, potatoes and sugar beets, and tree crops such as fruits. Cultivated and sown areas were reported by region and province. Production by the processed feed industry was described, including the roles of by-products and non-conventional feed sources. The China government does not publish statistics on the amount of grain fed to livestock. However, the authors utilized data from the U.S. Department of Agriculture on grain used for animal feeds in China.

China has a long history of utilizing non-conventional feed resources (NCFRs), crop residues and by-product feeds. NCFRs include a wide variety of substances including, for example, rice straw, azolla, cassava, banana rejects and maize stover. Examples of by-products include bagasse, brewers' grains, palm kernel cake, rice bran and poultry litter. As noted earlier, livestock in the Chinese dairy sector derived substantial fractions of their energy and protein-based feeds from crop residues and by-products, in systems where crops and livestock are tightly interlinked through transfers of biomass, energy and nutrients.

A feedstuffs availability model was developed and programmed as a spreadsheet. The model is based on the metabolizable energy and crude protein content of each crop, as well as grassland. The crop yield data are multiplied by sown areas to give total production, which is then multiplied by physical extraction rates – i.e. the proportions of each crop species comprised of grain, straw, brewers' grains, oilseed meal, etc. (for example, kg barley straw per kg grain) – to provide numbers of total quantities potentially available for both human and livestock utilization. Multiplication of the amount potentially available by the portion utilized by animals gives the total amount of feedstuffs that can be consumed by animals. The portions utilized were apparently estimated on the basis of expert knowledge. The proportions of oilseed meals utilized by animals are the products of subtracting estimates of losses due to transport and storage, animal refusal, waste, and use for fertilizer. A total of 38 crops, as well as four non-crop feedstuff sources (such as fishmeal), were considered. Each crop was partitioned into a primary output and any by-products or NCFRs. Grassland parameters included energy and protein contents, the extraction rate and area in hectares for five grassland types; warm, temperate, dry, arid and alpine. The inputted data from the approximately 1 000 parameters were then combined to calculate total energy and protein availability for livestock. Projections into the future were based on estimated growth rates in yield per hectare and sown areas.

Using this methodology, Simpson (2006) calculated that about 1.2 trillion Mcal of feedstuffs were produced in 2000. About 9 percent was derived from by-products, 13 percent from grasslands and 42 percent from grain crops. Non-conventional feedstuffs comprised 36 percent of all feed energy in 2000. About 800 million tonnes of residues and silage were calculated to have been produced in 2000, with residues accounting for 85 percent of that. The methodology was also used to assess China's beef production potential (Simpson, 2003) as well as consequences of potential changes in land use and agricultural productivities (Simpson, 2010b).

Long (2011) recently compiled and presented a number of statistics based on data from the Chinese Statistical Yearbook and other sources. These data show large increases in livestock-based food production and consumption. Per capita consumption of poultry and dairy both increased approximately 2.5-fold in the last 20 years. Red meat consumption increased from 21 kg/person in 1990 to 48 kg/person in 2009. Meanwhile, there was a significant decrease in food grain consumption. Small stock numbers increased 30–50 percent and dairy cattle numbers increased fourfold in the last 20 years. As a result of increased feed demands, China moved from being a maize exporter to an importer between 2000 and 2010. Annual soybean imports have risen from near zero to 50 million tonnes annually. Another consequence has been widespread rangeland degradation caused by overgrazing.

3.5 AFRICA

Use of crop residues in mixed crop-livestock systems

Crop residues (CRs) are roughages that become available livestock feeds after crops have been harvested. They are distinct from agricultural by-products (such as brans, oil cakes, etc.), which are generated when crops are processed (de Leeuw, 1997). A general consensus exists that there is enormous potential for better utilization of crop residues as livestock feed (Maehl, 1997). Crop residues are important in many national agricultural sectors, yet they are much underutilized at present. Ruminant livestock utilization of crop residues also contributes to the recycling of nutrients, and to soil fertility and structure, particularly in integrated farming systems. Cereal straws and stovers are by far the most important residues. National estimated residue yields were derived based on FAO production statistics for the production of food commodities (e.g. FAO, 1984, 1994), multiplied by factors as proposed by Kossila (1988). These multipliers can be replaced with more accurate estimates where possible.

Two kinds of ratios can be used to link grain and CR yield (de Leeuw, 1997). The first is a simple one in which grain yield is divided by an agreed factor expressing the harvest index, or proportion of grain to total above-ground biomass (Kossila, 1988). A second ratio is needed in relation to "edibility". To estimate the consumable fraction of a CR, data are required on parameters such as the likely removal rates by grazing animals or the refusal rates of stall-fed livestock.

Potential supplies of CRs in Africa (de Leeuw, 1997) can be approximated from country statistics on the proportion of land cultivated (e.g. World Bank, 1989; WRI, 1990), combined with yield estimates for the grains and tubers of the major crops (World Bank, 1989). These estimates are approximations and could be more accurate if better data for ratios of grain to CR were available. In Africa, restrictions on livestock access for CRs have become more common in recent years due to land privatization and intensification, so it can no longer be assumed that all of the potential CRs can be included in availability estimates.

3.6 SAHELO-SAHARAN REGION

Pastoral surveillance system and feed inventory in the Sahel

A Pastoral Early Warning System was developed by ACF (Action Contre la Faim) to monitor feed availability for pastoral livestock in the Sahelo-Saharan Region of Africa (Chapter 10). The system uses near real-time satellite imagery (vegetation greenness), ground data and livestock movement maps. Software has been developed to ingest and process these data to produce maps of feed availability in relationship to feed demands. A Normalized Difference Vegetation Index (NDVI) from SPOT 5 satellites is composited by VITO (Flemish Technologic Research Institute) over ten days at a 1 km x 1 km spatial resolution. VITO also produces a satellite-based Dry Matter Productivity (DMP) data product that is used.

A GIS overlay approach integrates the satellite-based vegetation data with additional spatial data characterizing accessibility of the forage to pastoralists and their livestock. A key constraint on availability is water, which may or may not be available within proximity to forage resources. Distance-to-water maps are used to determine which forage resources are sufficiently close to water to be utilized. Water availability maps are derived by combining remotely-sensed surface water maps with borehole maps. Water availability changes seasonally due to fluctuations in surface water. Availability is also constrained by unsuitable topography, particularly steep slopes.

Livestock distribution maps are then used to determine the distribution of feed demands. A simple feed balance is computed as the difference between feed availability and demand. In this way, areas of feed deficits can be readily identified, as well as areas of feed surplus.

The system is continually updated. At the end of each rainy season, a full feed inventory assessment is produced and made available to end users. ACF International intends to further develop the system and distribute it to countries in West and then East Africa.

3.7 SOUTHERN AFRICA

Development and application of Earth observation-based rangeland monitoring techniques in Namibia

The sparse network of rain gauges in parts of Southern Africa precludes a rainfall-based monitoring approach for forage biomass. Monitoring must, instead, be entirely based upon satellite data. A near real-time, satellite-based vegetation monitoring system called LARST (Local Application of Remote Sensing Technology) has been developed over the last decade (Chapter 11). The system is based on low cost satellite receivers that can download data from NOAA AVHRR (National Oceanic and Atmospheric Administration, Advanced Very High Resolution Radiometer) satellites. An antenna and receiver are set up locally and connected to a personal computer with the appropriate hardware and software. A methodology using a Vegetation Productivity Indicator (VPI) derived from such satellite data has been commissioned by governmental ministries in Namibia. The VPI is reported on a 10-day basis during the rainy season in map format and at the ministerial and agricultural district levels. The outputs are disseminated through workshop and training seminars and regular agro-meteorology bulletins produced by the Ministry of Agriculture.

A methodology has also been developed for combining satellite imagery (NDVI) with field observations of biomass for deriving near real-time maps of biomass estimates. Herbaceous biomass data are rapidly collected using a simple instrument called the disk pasture meter (DPM). Woody green leaf biomass is estimated using regression relationships with plant size, and by sampling plant size class distributions. Biomass is sampled along 1 km transects bisecting 1 km^2 sample sites. DPM readings are taken on both sides of the transect. The field biomass data are then regressed against the NDVI. The regression equations are then applied to NDVI maps to derive biomass maps.

3.8 MONGOLIA

Gobi Forage Livestock Early Warning System

A technologically advanced remote-sensing, GIS and simulation modelling system called the Livestock Early Warning System (LEWS) was applied to the Gobi pastoral region in Mongolia (Chapter 12). The LEWS combines field data collection from a series of monitoring sites, simulation model outputs, statistical forecasting and GIS to produce regional maps of current and forecast forage conditions. The system uses the PHYGROW[1] simulation model as the primary tool for estimating forage conditions. Field data, collected from monitoring sites established across the region, are used to parameterize and calibrate the model. Model runs for the monitoring sites are driven by near real-time climate data. The simulation model runs for each monitoring site are executed every 15 days and the outputs are made available via web portal (http://glews.tamu.edu/mongolia). To produce maps of forage conditions, the total forage available to livestock is output for each monitoring site and is co-located with remote-sensing imagery data (NDVI) data for the region and geostatistical interpolation is conducted to create regional maps of available forage. The LEWS system also incorporates a statistical forecasting system which provides a projection of available forage conditions for 60 days into the future (Chapter 12).

Climate data obtained from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA) are used as driving variables for a forage simulation model. The model predicts forage biomass for monitoring sites throughout the region on a daily basis, along with soil water balance and livestock grazing offtake. Permanent vegetation transects have been established throughout the region to obtain information needed to parameterize the model. A geostatistical mapping procedure, specifically co-kriging[2], is used to develop regional forage biomass maps, with model output being the primary variable, and remotely-sensed vegetation greenness being the secondary variable. To forecast probable future forage conditions, an auto-regressive integrated moving average (ARIMA) forecasting model is used, providing a 90-day forecast of forage conditions. Training is provided to herders, NGOs and other stakeholders in the use of the LEWS. The LEWS forage inventory is continuously updated through the use of current climate and remote-sensing data, as well as ground-based monitoring data. The system is to be adopted and institutionalized at the Mongolian Agency for Meteorology, Hydrology and Environmental Monitoring.

3.9 CHINA

Remote sensing and *in-situ* observation-based livestock feed inventory on the Tibetan Plateau

A model/remote sensing-based approach has also been taken to assess feed resources for pastoralists on the Tibetan Plateau (Chapter 13). Two models are used, one to calculate total vegetation productivity, and the other to calculate standing forage biomass.

The vegetation productivity model uses the Enhanced Vegetation Index (EVI) derived from the MODIS satellite. The data are downloaded from the U.S. Geological Survey (USGS) data centre. The spatial resolution is 500 m x 500 m and the temporal resolution is eight days. The VPM also uses remotely-sensed photosynthetically active radiation (PAR) from the TOMS (Total Ozone Mapping Spectrometer) satellite, and temperature data from the China Meteorological Data Sharing Centre. The model assumes that vegetation productivity is

[1] PHYGROW is a point-based, daily time step, algorithmic or computation engine that models above-ground plant growth, forage consumption and hydrological processes.

[2] Kriging provides a means of interpolating values for points not physically sampled using knowledge about the underlying spatial relationships in a data set to do so. Cokriging is an interpolation technique that allows one to better estimate map values by kriging if the distribution of a secondary variate sampled more intensely than the primary variate is known.

fundamentally limited by intercepted PAR. The EVI is assumed to be directly related to the fraction of PAR that is absorbed by the vegetation. The maximum light (PAR) use efficiency of the vegetation is a parameter. Light use efficiency is also affected by temperature, water and plant phenological status. CO_2 gas flux measurements are used to parameterize and validate the VPM.

The forage biomass model uses the EVI to calculate aboveground biomass (AGB). The relationship between EVI and AGB is determined empirically. Forage biomass is taken as some fraction of AGB, with the fraction being dependent upon grassland type, utilization (grazing) period, type of utilization and grassland degradation status.

3.10 UNITED STATES

National-scale rangeland resource assessments

By law, the U.S. Secretary of Agriculture is required to prepare an assessment of the renewable resources of forest, range and other associated lands every ten years (Joyce, 1989). As part of that mandate, comprehensive assessments of the U.S. forage situation have been carried out (Joyce, 1989; Mitchell, 2000). The assessments were comprehensive and broad, covering the entire gamut of ecological, agricultural, economic and socioeconomic aspects of the situation. With respect to assessing forage supply, a main focus of both assessments was on land areas that were available to grazers and rangeland health. In the 1989 assessment, it was stated that the national production of forage is difficult to quantify, and that forage production is a function of the available land, productivity and land management. The implementation of range technology has not been nationally inventoried, however. A forage production model was used in which previous estimates by the Soil Conservation Service (SCS) for range site class productivities were employed. These took into consideration range condition and proper use factors to estimate appropriate stocking rates in terms of animal unit months (AUMs). A different approach was used for forested areas. Hay production estimates from the U.S. Department of Agriculture (USDA) were used. On public grazing lands, the amount of land permitted for grazing and associated stocking rates were set by individual management units.

Importantly, grazing is one of many uses that must be considered. Grazing is balanced with needs for wildlife, biodiversity, ecosystem services and recreation. Sustainable land and natural resource stewardship is paramount. Rangeland health is "connected to the broader concepts of sustainability and sustainable management" (Mitchell, 2000). "The Montreal Process is one standard for evaluating rangeland sustainability at a national scale through seven criteria: biodiversity, productive capacity, ecosystem health, soil and water conservation, contribution to the global carbon cycle, multiple socio-economic benefits, and a legal-institutional-economic framework."

Given these considerations, it was possible to sum up the total AUMs permitted on public lands in the United States; total AUMs stocked on private lands could be calculated from national statistics. Based on these sources, it was calculated that, nationally, 86 percent of beef cattle feed came from non-irrigated private land, 7 percent from public land, 5 percent from crop residues and 2 percent from irrigated pastures. However, it was also concluded that national forage assessments are difficult because forage production is simply not inventoried (Joyce, 1989). The lack of ecological knowledge regarding factors determining forage production was acknowledged and it was recommended that there is need for a more comprehensive understanding of plant growth and its responses to environmental factors.

3.11 GLOBAL
Assessment using IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) and SLAM (Spatial Livestock Allocation Model)

A recent global-scale assessment of agriculture integrated three different models to assess the global human food situation and consequences for the environment (McIntyre *et al.,* 2009). They used IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) (Rosegrant *et al.,* 2002), a partial equilibrium sector model, to provide insights into long-term changes in food demand and supply at regional levels taking into account changes in trade patterns. The IMAGE 2.4 model (Eickhout *et al.,* 2006) was used to carry out environmental assessments. Terrestrial changes simulated by IMAGE were then used as input to the GLOBIO-3[3] terrestrial biodiversity model (Alkemade *et al.,* 2006)

Specifically relevant here, they used SLAM (Spatial Livestock Allocation Model) (Thornton *et al.,* 2002; 2003; 2006) driven by livestock supply and demand outputs from IMPACT. The main role of SLAM was to convert livestock outputs of IMPACT (number of animals slaughtered) into livestock equivalents by livestock system in order to estimate grazing intensities, which would then be used as input into IMAGE 2.4. Four classes of livestock systems were recognized: landless, livestock only/rangeland-based, mixed rain-fed and mixed irrigated. Livestock were allocated to the four systems based on agro-climatology, land cover and human population density (Kruska *et al.* 2003). Grassland-based systems were further broken down into climate zones (arid-semi-arid, humid-sub-humid, tropical highlands/temperate). The Global Land Cover (GLC) 2000 data layer (JRC, 2005) was used, along with the GRUMP (Global Rural-Urban Mapping Project) human population data set at 1 km resolution (GRUMP, 2005).

IMPACT was also used by Delgado *et al.* (1999) to assess world grain production relative to increased demands by livestock. They parameterized the model with crop areas, yield growth trends, herd size and productivity, and initial levels and trends in feed conversion. Parameters were drawn from econometric analyses, expert judgments and a synthesis of relevant literature. Herrero *et al.* (2009) used IMPACT to predict crop and livestock production, prices, water use, income and malnutrition. A second step of their assessment used GIS to reallocate country and food production unit level outputs from IMPACT to different livestock production systems within countries and regions.

A major effort to assess global ruminant production systems was also model-based (Bouwman *et al*., 2005). The IMAGE modelling framework (Alcamo *et al*., 1998) was used as a starting point. Modelled livestock production for 1970-1995 was based on FAOSTAT data on production, use and trade of meat, milk, eggs and other products by animal category. Other FAO animal production data sources were also used (Bruinsma, 2003; Sere &

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[3] GLOBIO is a modelling framework to calculate the impact of a number of environmental drivers on land biodiversity for past, present and future.

Steinfeld, 1996). Livestock feed requirements were derived from an existing energy balance model (EPA, 1994). Land cover maps used in IMAGE were used to estimate distributions of grassland and arable lands.

3.12 GLOBAL
Assessment of global human appropriation of net primary production (HANPP)

Much can be learned from efforts to assess how much of the annual biomass production by plants (net primary production, or NPP) is utilized by humans because a significant component of such assessments is the utilization of plant biomass for livestock feed. While these global-scale assessments may be relatively coarse to be of much use at a national level, global assessment methodologies are becoming increasingly fine-scaled, and are providing added details to spatial distributions of feed supply and use within countries.

The first attempt to carry out such an assessment (Vitousek *et al.,* 1986) did not attempt to calculate how much NPP is available for livestock feed, but it did calculate the amount that was probably used by livestock, as well as the fraction of total NPP used for feed. These authors used early estimates of global NPP that had been made by ecologists without the aid of modern GIS and remote-sensing databases. In their "low" estimate, which only included direct utilization, they relied on previous literature estimates of global livestock feed utilization (Wheeler *et al.,* 1981; Pimental *et al.,* 1980). In an "intermediate" estimate, they also included the amount of land converted to pasture for grazing, derived grazing lands (which accounted for 19 percent of total grazing land NPP), as well as anthropogenic fire losses. In their "high" estimate, they also included land lost to desertification. The rationale behind the intermediate and high estimates was that livestock require more plant material from the Earth's ecosystems than that simply counted as feed.

With the advent of GIS and remote sensing-based databases and models, it became possible to estimate the spatial distribution of NPP and its utilization over the Earth's surface (Imhoff *et al.,* 2004) more precisely. This analysis showed the uneven nature of human offtake, and the increasing importance of the movements of NPP products via imports and exports. This was useful for identifying areas of high impact (hotspots of sorts), areas of surpluses and deficits of demand compared with NPP, and thus implied "directions of net energy flow" spatially. From this, they could derive a "spatially explicit balance sheet of NPP supply and demand".

Imhoff *et al.* based much of their human food demands on FAO data, then used national level ratio of food demand to human population in combination with a human population map to create maps of demand. They used estimates of NPP from a global carbon model driven by remote-sensing data (Potter *et al.,* 1993; Slayback *et al.,* 2003). A review of other modelling assessments of global NPP can be found in Cramer *et al.* (1999). They estimated the amount of organic matter used as feed by applying efficiency values for grain (an average of 2.3:1 kg grain/kg carcass for all meat types) and for pasture (21.46:1 for ruminants) using data from previous studies. The total NPP required for grain feed was then calculated in the same way as for vegetal foods, adding residue and loss factors appropriate to each country's development status. It is worth noting that this approach is basically the same as calculating a feed balance and mapping it spatially, as is being done in some of the feed balance efforts reviewed in the case studies here (e.g. Chapters 10, 15).

The most recent assessment of HANPP was based on the best available global databases integrated in a high resolution GIS, used in combination with estimates of potential NPP from a dynamic global vegetation model called LPJ (Harberl *et al.,* 2007a, b). FAO statistical data (FAOSTAT) on livestock, agricultural yields and wood harvest at the country level were matched to a global land use map derived from a variety of GIS data sources. FAO livestock statistics were used to derive a feed balance for each country to calculate the biomass grazed that is not reported in the statistics. The NPP of the actual vegetation, including crops, was calculated by using LPJ to spatially allocate total NPP reported in the agricultural statistics. Cropland NPP was defined as the sum of harvested NPP, as reported in statistics and other fractions not accounted for in agricultural statistics. NPP of grazing land was calculated on the basis of LPJ runs that were modified to consider the effects of ecosystem and soil degradation, irrigation and fertilization. NPP utilized by grazing animals is not reported in agricultural statistics, so livestock feed balances were estimated on the basis of data on livestock numbers and livestock production from agricultural statistics (e.g. Wirsenius, 2003). Grazed biomass (offtake) was spatially allocated to grazing lands assuming it would be highest in the best-suited grazing areas and lowest in the least suitable ones.

In an assessment of the impacts of livestock on the global carbon cycle, Asner and Archer (2010) considered livestock feed utilization as just one of many of the impacts. They used satellite and modelling studies which estimated global NPP (Field *et al.,* 1998; Imhoff *et al.,* 2004) and determined the amounts of carbon fixed via primary production into crops and grazing lands (Sabine *et al.,* 2004), as well as the amounts of carbon actually consumed by livestock (0.45 Pg C/year), versus the total NPP including waste, seed production, allocation to roots and other ancillary flows (2 Pg C/year).