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The Impact of Industrial Grain Fed Livestock Production on Food Security: an extended literature review*

Final report

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Key Words: Livestock, Food Security, Intensification, Literature Review

COMPASSION in world farming ciwf.org

WSPA World Society for the Protection of Animals

Main Messages

Food security encompasses four dimensions: food availability, access, utilization and stability. Food supply and availability provide the framework condition, reductions in food availability most likely result also in reductions in food security. However, increased food supply (at the macro scale) does not necessarily improve food security. The notion of food security strongly builds upon a central aspect of sustainability, i.e. long-term viability.

Food supply is a central component of the biomass production and consumption system. Livestock systems represent a highly interlinked subsystem.

Despite the obvious links between food security and the livestock sector, and the anticipated changes in the livestock sector, only a limited number of empirical or conceptual analyses are available in the literature.

Livestock plays a central role for food security, directly through, for instance, food provision and risk avoidance, and indirectly, for instance, as a means of agricultural production and through providing employment, income, a capital stock, draft power, manure, and are beneficial for local nutrient cycles. Livestock can also negatively affect food security, in particular in cases when livestock feedstuff is made up from biomass that can also be used for direct human nutrition.

Production of meat, milk and eggs requires large amounts of animal feed. In general, livestock can feed on crop products (market feed), by-products and roughage (non-market feed). Trends towards industrial livestock keeping increase the demand for crop product feed.

The intensification of livestock production is associated with a decline of multipurpose use of live animals towards an exclusive focus on the food provisioning function (commodification). Industrial livestock systems are often associated with environmental impacts such as the disruption of local nutrient cycles, biodiversity loss, and local pollution of soils, water and air.

Animal products can provide an important source of nutritional energy, protein and micronutrients and are important inputs for physical and cognitive development and health. When diversified plant products are available, varied diets without animal products can be equally healthy. Overconsumption of animal based food is associated with several health risks, including heart disease, obesity and cancer.

Monogastric species, in contrast to ruminant species, have an overall smaller area requirement, but require more cropland; this can potentially lead to land use competition (food vs. feed production). Ruminants can graze on lands which are not or only hardly suitable for growing arable crops, but have a larger overall area requirement.

A switch towards more grain feedstuff increases the input output efficiencies of livestock systems, because grains have a higher nutritional value than roughage. However, it decreases the resource base of societies, as a major function of livestock can be seen in converting non-edible resources (e.g. grass, residues) into edible ones.

Expansion of cropland for increasing food and feed supply is often associated with detrimental ecological and social consequences, such as deforestation, pressures on pastoralists, reduction of subsistence, and land use conflicts.

Positive effects of increasing market orientation of livestock systems include rising income possibilities, enhanced production levels, and (potentially) a broadening of the subsistence base of smallholders. In particular dairy production is less subject to the disadvantages of economies of scale that favour large producers.

Negative effects of increasing intensification (that often goes along with market orientation), include the reduced ability of smallholders to participate in market, in particular related to production practices that show large effects of economies of scale (e.g. poultry production). Barriers to market participation for smallholders include high transaction costs, investment risks, and food safety regulations, in particular relevant for poor smallholders. Subsidies have a similar effect, as large producers often have a better access to subsidy systems.

The on-going structural changes in livestock systems put particular pressure on pastoralist societies, which currently consist of approximately 20 million households.

In developed nations, up to two thirds of total cereal production is used as animal feed. At the global level, maize is the feed grain number one; wheat and especially rice are only used to a small degree as animal feed. Oilseed cakes, by-products in the production of vegetable oils, form a crucial protein input for livestock feedstuff. A large share of this market feed is traded internationally.

The trend towards landless livestock systems, through (international) trade in feedstuff, increases interregional interdependencies throughout the world. With regards to food security this may increase vulnerabilities of many (developing) regions to world market price shocks.

The quantity and quality of human diets is a decisive factor for any future development. More modest diets, with a lower share of animal products, tend to keep the option space open at the cropland and grazing land level. In contrast, rich, animal-based diets reduce the option space, e.g. towards a more rigorous cropland intensification pathway.

Additional area requirements that would allow for livestock roaming in intensive systems are small in comparison to the area demand of feedstuff production.

Contents

Figures

Tables

1. Introduction

Providing the growing global population with food of sufficient quantity and quality while simultaneously safeguarding the natural ecosystems of the world is one of the sustainability challenges human society is facing. Recent decades have witnessed an unprecedented growth in human population and socioeconomic resource demand (UNEP, 2011), trends that are anticipated to continue over the coming decades. The world's population is projected to surpass 9 billion before 2050 (United Nations, 2011), inevitably calling for surges in the demand for food from plant and animal sources in the light of the current nutritional situation of the world population. As for today, approximately 1 billion people live under or close at the nutritional limits of a healthy and sufficient diet.

Demand for livestock products is forecasted to outpace the growth in population numbers, in continuation of the trends observable over recent decades. During recent decades, the share of animal products in human diets drastically increased, in particular in the developing world. The drivers of these trajectories are multiple, resulting from an intimate interplay of a large number of socioeconomic drivers, such as urbanisation, income growth, the liberalization of trade and capital and the global expansion of Western lifestyles (Steinfeld et al., 2010).

Concomitantly, animal production systems are undergoing complex processes of technical, geographical and functional changes at the global scale. Expansion of livestock production is a key factor and a major driver of deforestation, especially in Latin America, with massive impacts on global biodiversity and the global climate system (Steinfeld et al., 2006). Nevertheless, trends towards intensification and industrialization (and thus towards increased area efficiency) of the livestock system prevail at the global scale (Haan et al., 2010). In the course of these developments, extensive grazing systems that today collectively occupy huge land areas and sometimes lead to land degradation due to mismanagement are increasingly transformed and loose the many essential functions which livestock fulfils in subsistence dominated agricultural systems. Over the last century, livestock farming evolved from a means of harnessing marginal resources to produce items for local consumption to a key component of global food chains (Steinfeld et al., 2006; FAO, 2011a).

Today, although economically not a major global player, the livestock sector is socially and politically very significant. It accounts for 40 percent of the agricultural gross domestic product. It employs 1.3 billion people and creates livelihoods for one billion of the world's poor. Livestock products provide one third of humanity's protein supply, and are a contribution cause of obesity and a potential remedy for undernourishment (Seré et al., 1996; Steinfeld et al., 2006)

Along with intensification and industrialization go shifts in livestock species, with production of monogastric species (pigs, poultry) growing much more rapidly than the production of ruminant species (cattle, sheep, goats). Through these shifts, the livestock sector enters into more and direct competition for scarce resources such as land, water and energy (FAO, 2011a). In consequence, developments of the livestock sector are more and more directly interlinked with the issue of global food security.

The aim of this study is to provide insights into the complex interrelations between livestock, its changing market patterns and food security, at the global scale. On basis of a survey of recent scientific literature, the project aims at exploring the role of the growing and increasingly intensifying livestock sector for resource conflicts (e.g. an increased demand for cropland products for livestock production might decrease the availability of cropland produce for direct human consumption) in the context of global food security.

The survey provides a systematic assessment of the causal interrelations between livestock systems, feedstuff and food provision and so provides a ground for discussing the interrelations between livestock (change) and food security. The literature survey will be accompanied by an empirical scenario analysis for 2050 that quantitatively explores the framework conditions influencing the interrelations between livestock systems, dietary requirements and agricultural technology as well as their changes, at the global and continental scale. These modelling scenarios are built upon and continue the model development of an earlier project, documented in the “Eating the planet” study, co-commissioned by Friends of the Earth, UK, and Compassion in World Farming, UK (Erb et al., 2009a).

Interestingly, only a few studies exist, which explicitly address or empirically analyse the interlinkages between livestock (change) and food security. This is remarkable, given the central role of livestock for the provision of food and as an income generating sector, and the potential resource conflict of feedstuff for livestock production and food for direct human consumption. The interrelations between livestock and food security at the macro-scale was first addressed in the mid-nineties in seminal papers by Sanscoucy et al. (1995) and Fresco and Steinfeld (1998) from the international organizations FAO and ILRI. The publication of a current report by the FAO(FAO, 2011a), which explicitly elaborates on these interlinkage, was published during the concluding phase of this presented extended literature review (November 2011).

In order to derive insights into the complex interrelation between livestock (change) and food security, we here review literature on the concept of food security and the global food production-consumption system. In a subsequent chapter, we discuss different (typical) livestock systems and their sustainability challenges. From this perspective, we derive insights on the different roles that livestock systems play in the biomass production-consumption system and systematically explore aspects of the interrelation between livestock and food security. Results of the empirical analysis on the interrelations of diet changes, technology changes in agriculture and livestock production systems are explored in the following chapter, which is followed by a concluding chapter that summarizes the major insights from this extended literature survey.

2. Food security and the food system

2.1. Food security

In order to explore the interrelation between livestock changes and food security, it is important to first elaborate on the concept of food security and the many aspects of food-insecurity in the context of the food system. The food system includes a wide range of activities, from planting seeds and agricultural management to disposing of household waste; thus, it encompasses the full spectrum from agricultural production to the consumption and the disposal of final biomass products (that is: processors, businesses, policy, and other resources).

The term *Food Security* has its origins in the first World Food Conference in 1974, hosted by the FAO in Rome, and has evolved since. According to its original and very general notion, food security is given when

> "*… all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Household food security is the application of this concept to the family level, with individuals within households as the focus of concern* (FAO, 2010)."

Following this definition, food security can be addressed on various spatial levels, from the global level, national level to the community or household level. The notion of food security explicitly addresses current status and future developments (*"at all times"*), as well as equity aspects (*"all people"*), and is thus in line with the general notion of sustainable development (WCED, 1987). More recently, the ethical and human rights dimension has come into focus (FAO, 2006), based on the UN declaration on human rights from 1948, and currently 40 countries have the right to food explicitly included in their constitution. Note, however sustainability aspects related to the local production-consumption systems, such as livelihood or issues of animal welfare, are not included (yet) in the food security concept.

Although the FAO definition of food security is widely used, many ambiguities related to exact definitions of food security and on differences in the focus of the varying aspects of food security remain. The body of literature on food security can be classified according to their major focus on different aspects:

(a) Distributional issues (e.g. Drèze and Sen, 1991; Timmer, 2000; Chappell and LaValle, 2009).

(b) The amount of overall food supply (e.g. Beddington, 2010; Godfray et al., 2010a).

(c) Access to food (e.g. Alexandratos, 1999; Nature Editorial, 2010).

(d) Sustainable intensification – ie. increasing yields without adverse environmental and social impacts - for increasing food production and food security (e.g. Chappell and

LaValle, 2009; Ericksen et al., 2009; McIntyre et al., 2009; The Royal Society, 2009; Beddington, 2010).

(e) Food sovereignty. Food sovereignty denotes the ability of population to provide sufficient food (regardless if imported or produced domestically) for themselves. This notion of food sovereignty is widely used by the international peasants network Via Campesina to describe the right of communities to define their own agricultural and food policy (www.viacampesina.org).

(f) Nutritional security. In response to mainstream perspectives on food security that focus on the supply side (main question: Is there enough food?), Pinstrup-Andersen (2009) introduced the term *nutritional security*, in order to cover aspects such as the possibility to live a healthy life, a concept that also includes e.g. access to water or good sanitation conditions.

At regional and national levels, food security is often operationalized by calculating national or regional food balances, i.e. balances between food availability, resulting from domestic production and imports, and food demand, assessed on the basis of assumptions of per capita requirements. At this level, the focus is clearly placed on the issue of food availability.

At the household level, food security is equated with sufficiency of household entitlements. Household entitlements bundle food production resources, income available for (food) purchases, and assistance sufficient to meet the aggregate nutritional requirements of all household members. Food security in this notion largely relates to assumptions of minimum nutritional requirements.[1] Food security at the level of the individual is rarely, if ever, considered (Chen and Kates, 1994; Sansoucy et al., 1995; Pinstrup-Andersen, 2009).

2.2. The food system

In order to tackle the multi-dimensional nature of food security, a conceptual framework that includes economic, social, cultural and biophysical factors is needed. Such a concept is presented by GECAFS (Global Environmental Change and Food Security), an international scientific programme for the study of food security. The programme was jointly initiated by the IGBP (International Geosphere Biosphere Programme), IHDP (International Human Dimensions Program for Global Environmental Change) and WCRP (World Climate Research Programme) and terminated in March 2011 (now partners of the Earth System Science Partnership ESSP). It focussed on understanding the links between food security and global environmental change. The main objective included determining strategies to cope with the impacts of global environmental change on food systems and assessing the environmental, socio-economic and cultural/ethical consequences of adaptive responses.

[1] Even though it is a highly controversial figure, the World Food Programme of the United Nations defines 2100 kcal/cap/day as a minimum energy requirement assuming standard population distribution, body size, a warm climate, pre-emergency nutritional status and light physical activity (WFP 2000). However, as this figure depicts an average value, it does not cover disproportionate nutritional requirements and distributions within households.

GECAFS grouped scientific expertise and brought the integrated character and multiple dimensions of the food systems to the attention of global environmental researchers (Ericksen et al., 2009). According to this notion, food systems encompass four sets of activities (Ericksen et al., 2009; Ingram et al., 2010): (i) producing food, (ii) processing food, (iii) packaging and distributing food, and (iv) retailing and consuming food. These activities lead to a number of outcomes, related to food security, environmental and social welfare concerns. These outcomes can be in a trade-off or synergistic relation to each other (Figure 1).

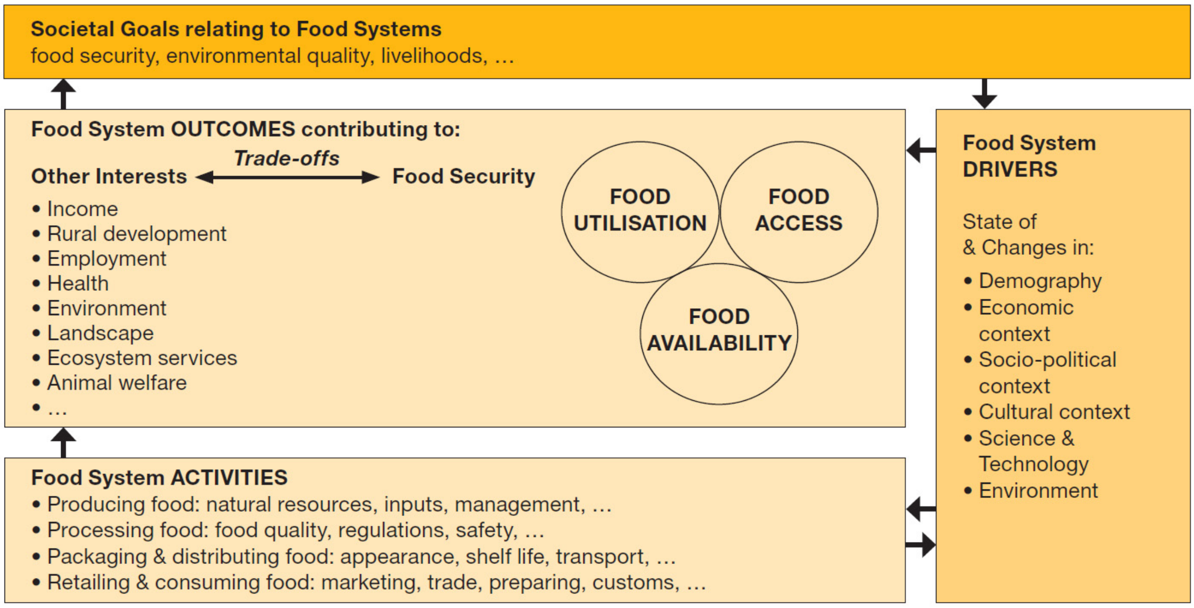


Figure 1. Key drivers, activities, outcomes, and feedbacks in the food system (from Ericksen, 2008; Ingram, 2009). According to this notion, food security is the principal societal goal of food systems.

Food security is denoted as a major objective of the food system. In overall terms, the outcomes of the food system relate to the balance of food security and other parameters, such as income, employment, health, animal welfare or the use of biomass for other than human nutrition purposes (fuel and fibre). Interactions between and within biogeophysical and human environments influence both the activities and the outcomes (see Figure 1). Thus, food systems encompass social, economic and political as well as ecological issues. Food systems, however, are shaped and influenced by various societal and environmental factors. For example, the size and composition of a population, income and its distribution, political conditions, education, cultural and religious traditions impact on the possibility for humans to meet their daily nutritional requirements.

Following this encompassing notion of the food system, food security relates to the following aspects (based on Ingram, 2009):

1. **Food availability** refers to the supply side of food; it considers the amount of food produced, distributed and exchanged, that can be consumed by a certain entity; at the individual, the household, the regional, or the global level. Ingram et al. (2010) discern production (i.e. local agricultural production), distribution (the amount of food that is physically moved to consumers) and exchange (the amount of food that can be obtained through exchange mechanisms such as trade). Production is linked to issues

like raising yields (and therefore, closing yield gaps), intensification of production and land expansion. Scholars that focus on this issue suggest that raising food production increases food security, a prominent perspective. Sustainable intensification, increasing yields while at the same time avoiding negative ecological and social effects, is commonly propagated (Tilman et al., 2002; Baylis and Githeko, 2006; Flint and Woolliams, 2008; Godfray et al., 2010a, 2010b; Foley et al., 2011).

2. **Access to food** relates to distributional issues of food security. Ingram (2009) subsumes distributional issues under the term with the aspects (a) affordability, (b) allocation and (c) preferences. Affordability addresses the purchasing power of households, prices of food, and the amount of household income that is spent for food. Allocation refers to when, where and how food can be accessed by consumers, mostly through markets. Consumer's preferences are social and cultural norms that influence the demand for certain types of food. Authors that focus on distributional factors mostly address the need for an equitable distribution of food (Chappell and LaValle, 2009), and the affordability and accessibility of food (Alexandratos, 1999; Hazell and Wood, 2008). Other issues of accessibility and affordability, such as the seasonal availability of food (e.g. according to rain and dry seasons in drylands) and linked issues such as adequate storage facilities for food, are only rarely addressed in the literature. Nevertheless, the role of natural disasters, climate variations, or economic collapses, conflicts or war which cause temporal or transitory food insecurity are discussed (Reutlinger, 1986; FAO, 2011a).

3. The third aspect, **food utilization**, refers to nutritional value, social value, and food safety issues (Ingram, 2009). Nutritional value refers to how much of the daily dietary energy requirement can be reached and the composition of this daily intake. Within the GECAFS scheme, nutritional value also refers to disease, incidence (which affects food absorption), education, facilities for cooking and preparing food, access to clean water, and hygiene practices. Some authors refer to this aspect as meal security, as these are the practices that have the most direct influence on the human body. For example, Pinstrup Anderson (2009) denotes the importance of the availability of water and of certain standards of sanitation for the digestion of food. Social and cultural aspects of consumption include the ways food is prepared, consumed (alone, in groups, time of the day etc.), and which kind of food is highly valued – eg. locally or organic produced food. Food safety refers to risks that stem from the addition of chemicals, genetic modifications or antibiotics during food production. EHEC, Salmonella, or Bovine spongiform encephalopathy (BSE) are examples. Beside these risks that mostly concern industrial livestock keeping, food safety also includes accidental contamination of foods with fungi or bacteria during production, storage or transport of livestock products.

The GECAFS scheme provides a holistic approach that enables the linking of drivers and activities within the food system with food security. This approach is particularly suited to identifying and analysing trade-offs between different aspects of FS and environmental concerns, e.g. the expansion of agricultural areas for food production can trigger deforestation

(Ingram et al., 2010). On the other hand, synergies can be found as well: increasing food security is beneficial to health and rural development.

FAO pronounces the importance of a fourth pillar, **stability**. This aspect of food security focusses on the temporal aspect: food security requires access to adequate food at all times, and thus relates to terms such as risk or vulnerability. The concept of stability refers to both the availability and access dimensions of food security. According to FAO, all four pillars are considered to be of equal importance and thus require equal attention when discussing food security (FAO, 2006)

2.3. Critical factors related to food security

The role of policy measures appropriate for raising food security in developing countries is still a matter of debate. Specific policy measures focus on different aspects of food security and often combine sustainable agricultural and rural development goals with the goals of food security enhancement (FAO, 2006). Land availability is considered to be a critical factor for achieving food security, although it is neither the only nor always the most important aspect (UN, 2001a in Ingram et al., 2010). However, as future production growth will mainly depend on increases in yields, and expansions of cropland will only play a subordinated role (Bruinsma, 2003; Millennium Ecosystem Assessment, 2005a; McIntyre et al., 2009), this focus often includes availability of means and options to close the observed large yield gaps in many developing countries (yield gap denotes the difference between maximum and average yields achieved in a region; Alexandratos, 1999; Beddington, 2010; Godfray et al., 2010a; Woods et al., 2010; Foley et al., 2011). Such simple strategies aiming at increasing production for decreasing food-insecurity are, however, contested, based on the simple fact that the number of undernourished people did not significantly decrease (and even remains constant since 1990) despite the immense success to increase agricultural production over the last decades (Evenson and Gollin, 2003; Thurow and Kilman 2009, Skoet and Stamoulis 2006).

Many policies that aim to improve access to food are focussing on improving the access to markets, by subsidizing agricultural production (Alexandratos, 1999), which consequently may result in higher incomes and decreased food prices for low income earners. In this notion, access to markets not only includes the possibility to buy food, but also access to technology to enhance production, infrastructure to trade, store and distribute food, and education (McIntyre et al., 2009; FAO, 2010). Finally, increasing biomass use efficiency, by decreasing losses from the food production chain, is also seen as a means to enhance food security (Parfitt et al., 2010; Foley et al., 2011): this perspective builds upon the notion that approximately 40% of the food produced are lost due to deficient transport or storage conditions in developing countries. In industrialized countries, losses are smaller in the production and processing chains, but higher at retail or consumer levels. Reducing these waste flows is seen as an efficient strategy to increase food security in developing countries (FAO, 2011a).

Some argue that the separation or specialization of the various production processes can increase its efficiency. A country that trades for products it can get at a lower cost from another country is better off as if it had produced these commodities itself (the notion of comparative advantage by David Ricardo, see Dewald and Weder, 1996; Andrea, 2004). A greater specialization encourages the promotion of trade. Countries produce goods where the opportunity costs are low. Trade allows regions with high population densities and environmental pressures to dislocate certain elements of the production chain to distant territories, with lower environmental pressures and population densities. For instance, livestock producers in parts of Asia and Europe purchase feedstuff from the Americas and Brazil (Galloway et al., 2007). However, this specialization requires low transport costs.

National subsidy systems influence trade patterns between developing and developed countries. Most developed countries offer subsidy payments towards domestic agricultural production. Through these subsidy payments, farmers have an incentive to produce agricultural products even during times of excess supply. This excess supply, if dumped on international markets for a low price, has a high potential to drive down world prices of agricultural goods, with far reaching effects on food security in developing countries.

On the one hand, a low price of agricultural commodities can improve food security for consumers in developing countries which themselves do not have access to land, by providing cheap food (Khamfula and Huizinga, 2004). Countries can so buffer their excess demand and export it to countries with supply shortages. This increases the export country's national balance of payments and results in an increased level of welfare (FAO, 2011a).

On the other hand, low world prices may affect farmers in developing countries who only rarely receive subsidy payments and cannot compete with the low world market prices, as they do not allow for covering the production costs FAO, 2011a. In particular small-scale farmers in developing countries cannot match high quality and low prices of the imported goods, resulting in decreases of food security FAO, 2011a. Protective policy measures such as tariffs have are often seen as a counter measure, as it allows developing countries to artificially influence the price of the imported goods that result in a contraction of domestic demand and an expansion of domestic supply. This results in a net effect, where the amount of goods imported is reduced and the government receives tax revenue from the tariff payments. However, within FTAs (Free Trade Areas) setting up tariffs is not permitted. In such cases, however, countries without subsidy payments can suffer disadvantages from free-trade agreements (van Beers and van den Bergh, 2001; Schiff and Winters, 2003).

The FAO argues that the prices of imported goods do not have an impact on small-scale farmers with no market access as these are only sold in cities or where farmers have access to the market. They suggest connecting small-scale farmers with markets by contract farming, building coops or by the establishment of niche markets FAO, 2011a.

2.4. Livestock’s role in the food system

Livestock plays a central role in the food system and thus for food security. Animals represent an important source of food, which balances against the amount of cropland based feeds they eat – these two factors interrelate and influence food security in opposite directions. Animal products such as meat and milk are rich in high-quality protein, minerals, vitamins and micronutrients. The overall nutritional value of animal protein is higher than that of staple food (e.g. cereals, roots and tubers). Therefore, even small amounts of animal products can correct amino acid deficiencies in cereal-based human diets. Furthermore, animal source proteins are more digestible and metabolized more efficiently than plant proteins (Sansoucy et al., 1995; Neumann et al., 2010). However, for calorie intake and many nutrients, plant based foods are nutritionally preferable. If over-consumed, animal products pose a health threat due to e.g. the high share of saturated fats. As for today, more people (over 1 billion) suffer from obesity related malnutrition (including from meat) than from hunger related malnutrition.

The livestock system, comprising monogastric (e.g. pigs, poultry) and ruminant species (e.g. cattle, sheep, goats) is a central element in the biomass production-consumption system. As a consequence, changes in the livestock system(s) have far reaching effects on food systems. Figure 2 illustrates the different components of the biomass production-consumption system and flows of biomass (primary, secondary or wastes) between them.[2]

The livestock sector receives inputs of edible plants as well as fodder, either from domestic or foreign sources. A significant input of the livestock system consists of residues from vegetal food production (e.g. beer and oil production, domestic and imports). Outputs of the livestock system are consumed as food, are exported or lost (wastes). Before the BSE crisis, re-use of animal wastes represented a vital input to the system, now almost completely replaced by vegetal market feed, in particular by soy cake (Elferink et al., 2007). An ‘internal’ flow is the output of milk to raise young livestock, mostly relevant for ruminant systems.

Monogastric and ruminant systems differ considerably regarding their feed requirements, due to the anatomic differences of the livestock’s digestive systems (monogastric species have a simple, single-chambered stomach, ruminants have a four-chambered complex stomach; therefore, ruminant can digest complex molecules such as grass fibres, which monogastric species cannot digest). Ruminant species can be fed exclusively from roughage. Increasing feedstuff quality with cropland-based food (e.g. grains), or from nutrient rich residues from processing (e.g. oilseed cakes) can reduce total feed requirement of ruminants significantly and so improve input-output efficiencies. However, there exist upper limits on the fraction of non-roughage feedstuff in the overall feed supply that, if exceeded, lead to diseases or endanger animal welfare (FAO, 2011a). In contrast, monogastric species can be exclusively fed with high-quality feedstuff usually from cropland and roughage plays as subordinate role.

Thus, monogastric species naturally feed on a feedstuff that is closer to a human diet. Extensive livestock systems are systems where animals find a large proportion of their feed from sources not edible to humans, such as grasses and insects, harvest residues and kitchen

[2] This schematic also represents the core of the biomass balance model developed in the earlier project (Erb et al., 2009a) and allows to consistently link production and consumption scenarios.

waste. In intensive systems, animals are usually fed feedstuff that includes primary crops such as cereals, soya, but also fishmeal as well as roughage. Intensive poultry and pigs are the biggest consumers of grain and protein edible by humans, although both have been bred to be efficient feed converters (FAO, 2011a).

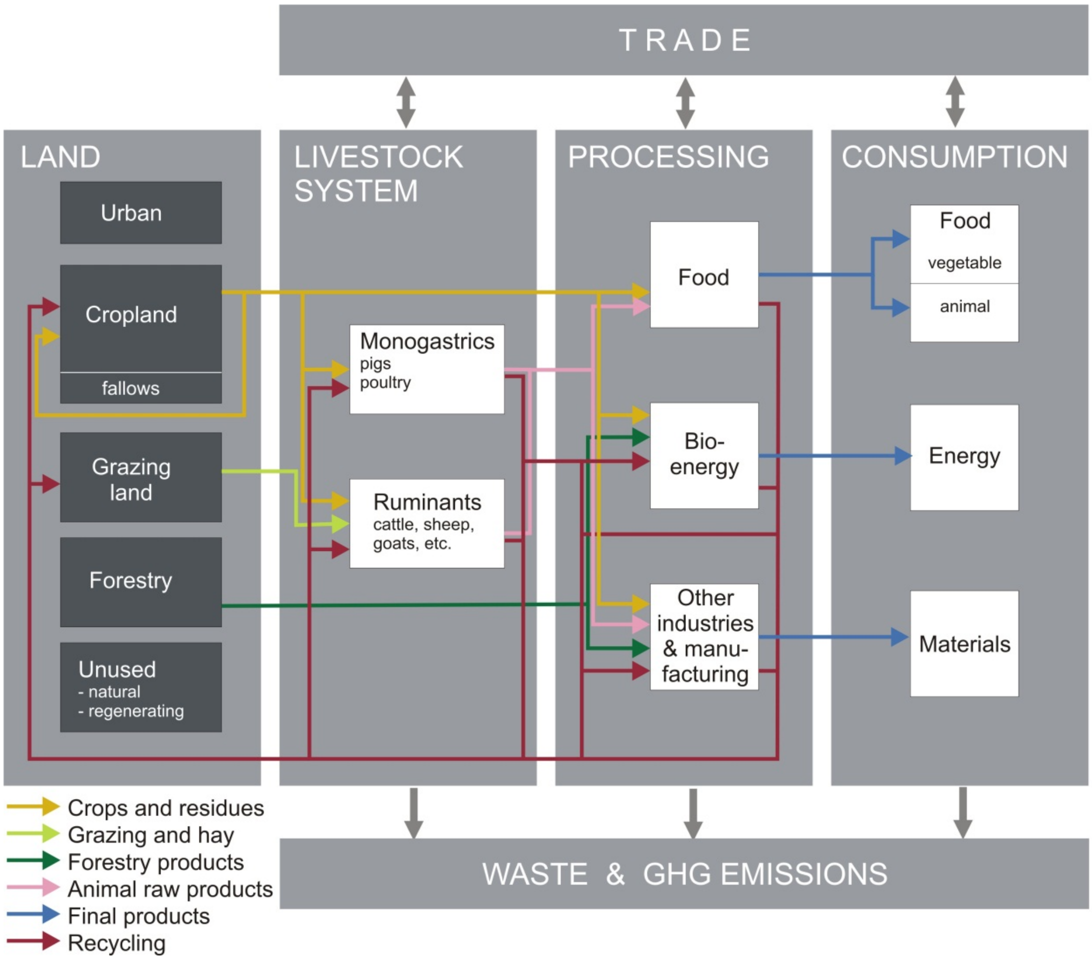


Figure 2. Material and energy flows in the biomass production-consumption system. This system comprises essential components of the „food system activities“ by Ericksen, 2008; Ingram, 2009). Livestock plays a central role in the system, representing a subsystem that converts inputs (primary or secondary) to outputs (such as food or manure), which serve as inputs for other subsystems.

Figure 2 illustrates that input flows as well as output flows of the livestock system are in close connection with other flows in the biomass production and consumption system. Produce from cropland can either flow directly to processing for human food or be used as an animal feedstuff. Wastes and residues from processing are significant inputs to the livestock system that can substitute considerable amounts of direct inputs. Outputs of the livestock sector, products and wastes, go to food (meat, milk, eggs, etc.), energy (e.g. manure for biogas) and material processing (e.g skins and hides) and interact with other direct flows from land or processing. An important fraction of livestock wastes flows back to the land compartment in the form of manure, and represents a vital input to conserve soil fertility, but can also result in water and soil pollution. Trade, which interlinks with the livestock system, processing and consumption, also plays a vital role in the biomass production and consumption system, which will be explained in a latter section.

3. Livestock systems

Given the central role of livestock in the food system and the many relations to food security, it is surprising that the body of literature addressing explicitly this interrelation is so scarce. In order to systematically explore the role of livestock and the impact of changes in the livestock sector on food security, we start from classification schemes of global livestock systems. At this level of information, literature allows us to derive information on sustainability issues related to livestock systems, and to indirectly derive information on the relation between livestock change and food security on a global level.

An extensive body of research exists on livestock classification systems. A standard on livestock classification systems was developed by Seré et al (1996).[3] This classification system is currently the standard system for livestock typologies, used by international institutions such as the FAO, ILRI (International Livestock Research Institute) and many authors. The most elaborated global analysis based on this classification system was conducted by Thornton et al. (2002). Numerous subsequent publications use basically the same classification system, introducing only minor amendments or new class separators (Blench, 2001; Kruska et al., 2003; Wint and Robinson, 2007; Herrero et al., 2009; Steinfeld et al., 2010; Thornton, 2010).[4]

Two major groups of farming systems are discerned in this system: livestock systems that exclusively rely on livestock production (grassland based and landless systems) and systems that combine livestock and crop production (mixed farming systems). The first group is separated in systems that are land-based, i.e. the livestock is fed predominantly from farm-owned or cultivated land, and landless systems, which rely to a large extent on off-farm produced feed. The land-based group (solely livestock grassland based and mixed systems) is split into sub-groups, on the basis of agro-climatologic information, i.e. the agro-ecological zones classification by the IIASA and the FAO (Fischer et al., 2001). These systems are outlined below[5]:

1. "Solely livestock production systems (L). Livestock systems in which more than 90 percent of dry matter fed to animals comes from rangelands, pastures, annual forages and purchased feeds and less than 10 percent of the total value of production comes from non-livestock farming activities.
    a. Landless livestock production systems (LL). Subset of the solely livestock production systems in which less than 10 percent of the dry matter fed to

[3] Numerous authors refer in their studies (e.g. Steinfeld et al., 2006) to an update of the classification system by Seré et al., (1996), "Groenewold 2005". Unfortunately, this study, which should contain more up-to-date quantitative information, is not publicly available and seems to be for internal use only.

[4] Kruska et. al (2003), for example, differentiates between urban landless systems and landless systems in non-urban areas with high population densities.

[5] See (http://www.fao.org/DOCREP/V8180T/v8180T0y.htm)

animals is farm-produced and in which annual average stocking rates are above ten livestock units (LU) per hectare of agricultural land. This class is separated in monogastric and ruminant based production.

   b. Grassland-based systems (LG). Subset of solely livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten LU per hectare of agricultural land. This class is further differentiated in classes "Temperate Zones and Tropical Highlands", "humid and Sub-humid Tropics and Sub-tropics", and "Arid and Semi-arid Tropics and Sub-tropics". This class is sometimes also split into two groups: intensive and extensive grazing systems (Thornton et al., 2002; Steinfeld et al., 2010).

2. Mixed-farming systems (M). Livestock systems in which more than 10 percent of the dry matter fed to animals comes from crop by-products or stubble or more than 10 percent of the total value of production comes from non-livestock farming activities.

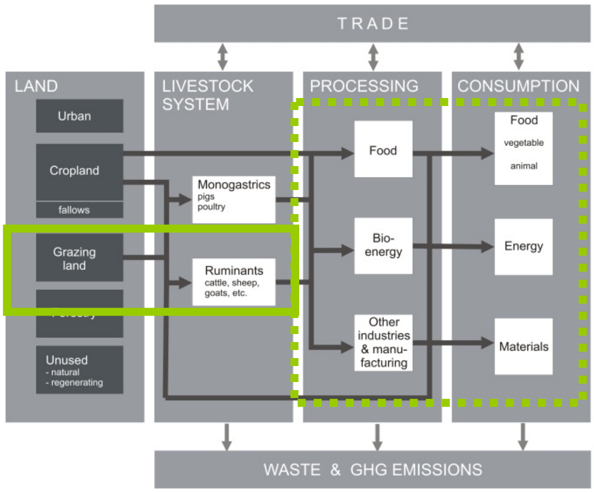
   a. Rain-fed mixed-farming systems (MR). A subset of the mixed systems in which more than 90 percent of the value of non-livestock farm production comes from rain-fed land use.

   b. Irrigated mixed-farming systems (MI). A subset of the mixed systems in which more than 10 percent of the value of non-livestock farm production comes from irrigated land use."

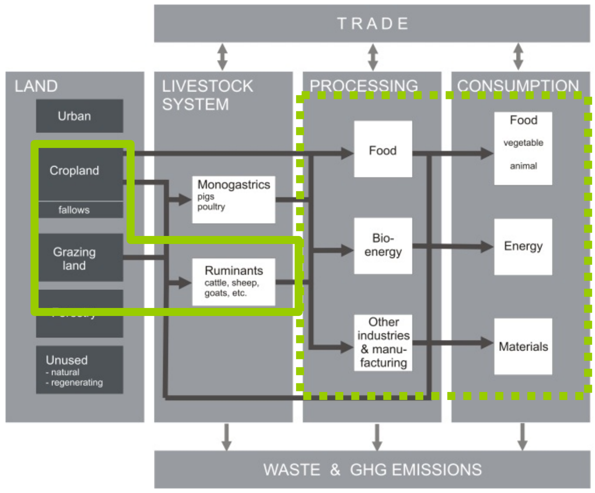
The two mixed classes are further split into the three groups ("Temperate Zones and Tropical Highlands", "Humid and Sub-humid Tropics and Sub-tropics", and "Arid and Semi-arid Tropics and Sub-tropics"). This results in an overall classification with 11 livestock systems. Figure 3 illustrates the major differences between the livestock systems on the basis of the biomass production and consumption system presented above.[6]

[6]. Reading example: Figure 3a shows that in a system where only livestock is produced, market oriented production will encompass ruminants and their respective grazing lands from which the animals are fed (line). Subsistence farming additionally encompasses processing and consumption stages (line plus dashed line).

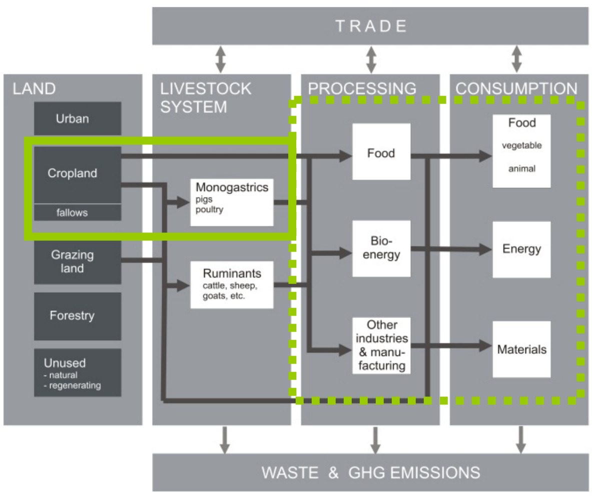
a) Livestock only. Market oriented (line) or subsistence (line plus dashed line)



b) Mixed ruminant. Market oriented (line) or subsistence (line plus dashed line)



c) Mixed monogastric. Market oriented (line) or subsistence (line plus dashed line)



d) Landless – market oriented (only rare: ruminants; dashed line)

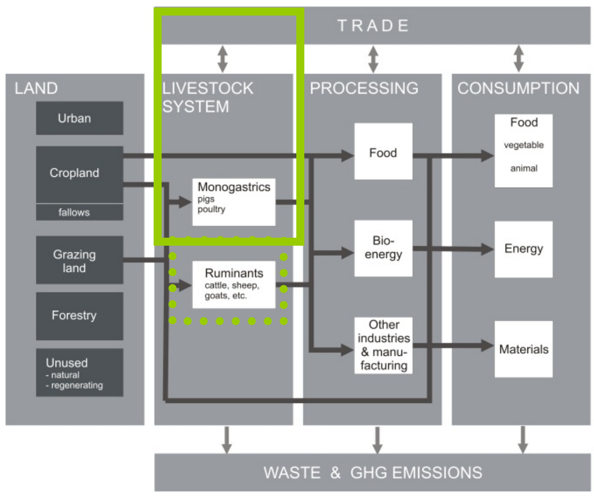


Figure 3. Typology of livestock systems and their position in the biomass production-consumption system

3.1. Global distribution of livestock systems

Figure 4 displays the geographic distribution of the major livestock systems in a global gridded map. Landless production systems play a significant role at the regional scale, mainly in industrial centres of North America, Northern Europe, in the production centres of NAWA countries, and also in South- and South-East Asia. In contrast, mixed systems are found across almost all regions and biomes. Grazing systems dominate in fringes to cold or hot deserts and semi-deserts, tropical rain forests, and in large areas in Sub-Saharan Africa.

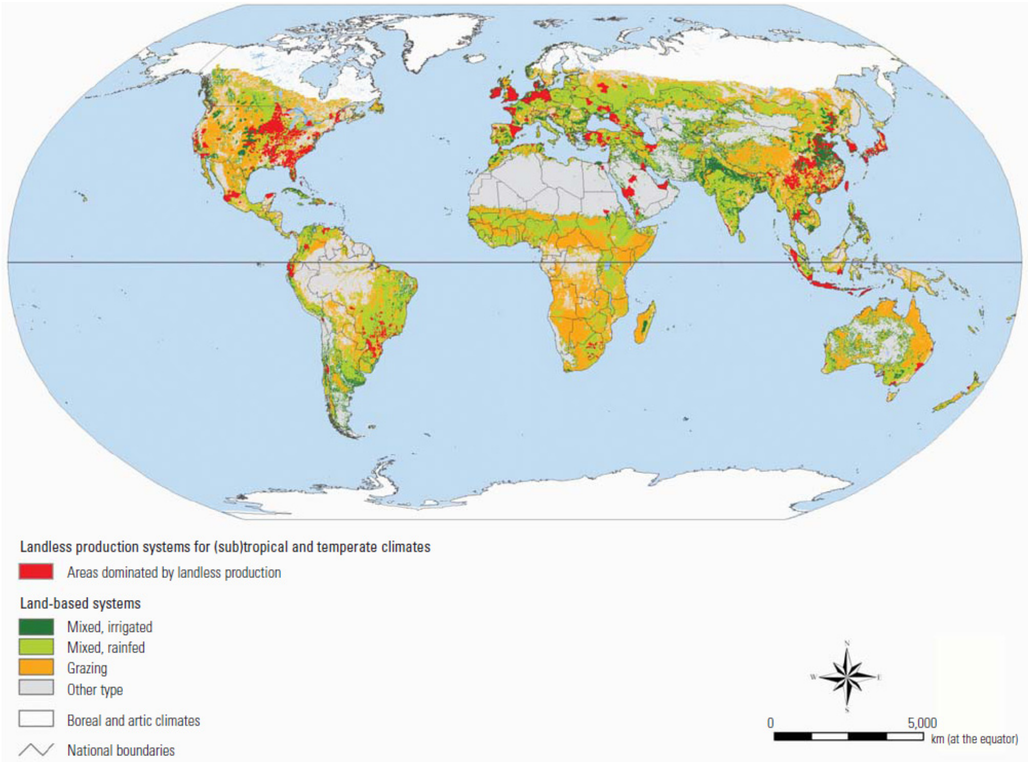


Figure 4. Geographic distribution of major livestock systems, from Steinfeld et al., 2006

Seré et al. (1996) calculated for the year 1991 the number of people living under different land based livestock classes (see above). Distinguishing six different regions (Sub Saharan Africa, Asia, Latin America, Northern Africa and Western Asia, CIS and Eastern Europe, the OECD (excluding Turkey), and other developed countries), they classified the regional population according to the dominant system (for methodological details see Seré et al., 1996). Figure 5 shows their results.

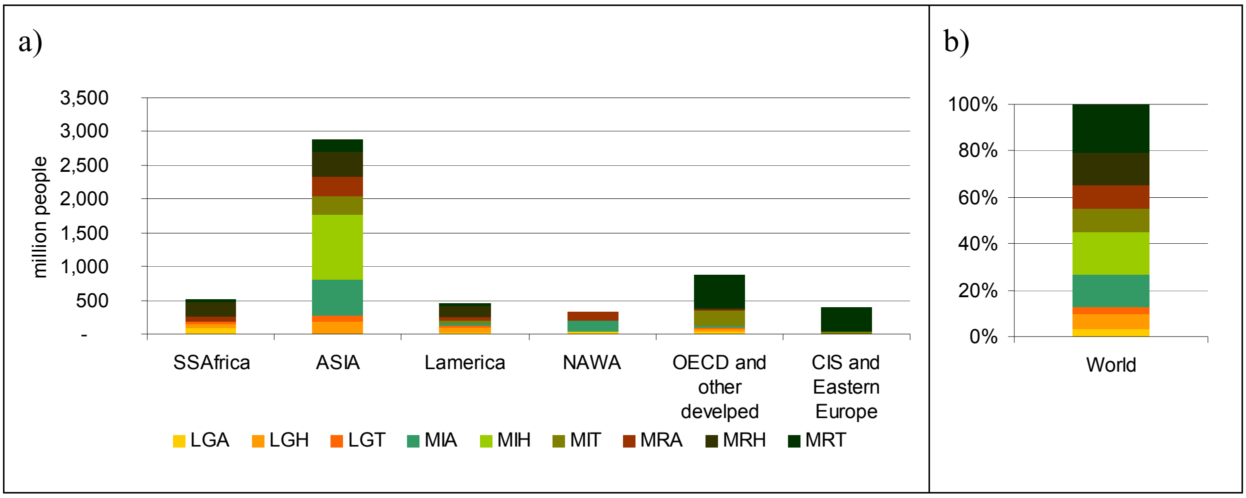


Figure 5. Global population in different livestock systems a) numbers per region (in million people), b) percent of global; LG: livestock-based, grazing only; MI: mixed irrigated, MR: Mixed rainfed. A: arid, H: Humid, T: temperate. Source: Seré et al. (1996). Note that this classification scheme does not allocate people to land-less systems.

On a global scale, 12.9 % of total population were living in grassland based livestock only systems in 1991. In absolute figures, around 280 million people were living in Asia, 170 Million in Sub Saharan Africa and 130 million in Latin America. The relative importance of these systems was highest in Sub Saharan Africa with a share of around a third of the population. The largest share of the global population was living in mixed irrigated systems, with a share of 42 %. This livestock system was dominating in Asia, here comprising mostly mixed rice-livestock systems. Mixed rainfed systems were having a somewhat larger global share (45%), dominating in industrial or transition regions. Also in Sub Saharan Africa rainfed-mixed systems were dominating, reaching a share of 66% of the total regional population.

For the developing world, Thornton et al. (2002) estimated a total of 180 million people depending on grassland based livestock systems for the year 2000 (see Annex). Interestingly enough, this is with 4 % of the total, considerably lower than the estimate of Seré et al. (1996; see above).[7] 81 % of people living in developing countries were living in mixed crop livestock systems, 15% in landless systems. A disproportionately high share of poor livestock keepers were living in grassland based livestock only systems. The share of poor livestock keepers in other systems was relatively low in comparison to the total number of people. The largest share of poor livestock keepers was living in mixed rainfed systems (arid or humid areas), with a total share of 53 % (see Annex). However, these numbers are contested, mainly due to the intricacies related to economic evaluations of wealth for pastoral systems (Davies et al., 2010).

[7] It is not clear if this discrepancy can be interpreted as a reduction of the size of this livestock system in the period between the two publications of Seré et al., 1996 and Thornton et al., 2002. Rather, it is more plausible that this discrepancy is based on different definitions.

3.2. Sustainability issues related to the livestock systems

The livestock systems differ substantially in their typical feeding efficiencies (i.e. input to output ratios) and stocking densities (i.e. number of animals per area; Grigg, 1974; de Vries and de Boer, 2010). Furthermore, the different classes are characterized by typical sustainability issues that also link to food security. The main characteristics of the systems are summarized below.

3.2.1. Landless systems (LL)

These systems are dominant around the urban conglomerates of East and South-East Asia and Latin America or near the animal feed-producing or feed-importing areas in Europe and North America, such as large ports. These systems typically consist of a single species, in particular pigs or chickens. Ruminants are in general not kept in landless systems. LL systems are rapidly growing (monogastrics for their higher efficiencies), as demand for livestock products (meat, eggs, milk) rises in these countries.

LL produce about 72% of the global poultry and 55% of the pork meat, and around two thirds of global eggs supply (Seré et al., 1996). Concerning beef production, these systems are not very significant worldwide (5%).

Major environmental concerns relate to the generation of waste (manure concentration), air and water pollution (also see Naylor et al., 2005). Where these systems prevail, most households are food-secure, but as these systems can produce livestock products cheaply, they impose a threat to smallholders who desire to enter markets too. These systems are often associated with issues of animal welfare.

Another major problem for these systems are livestock and poultry diseases (Steinfeld et al., 2010, Chapter 11). There are also constraints to animal production, e.g. feed and water availability.

3.2.2. Grassland based systems (LG)

Grazing systems cover the largest global area. They currently occupy around 26% of the earth's ice-free land surface (Steinfeld et al., 2006). These systems are present across a wide range of agro-ecological gradients, characterized by differing levels of biological productivity of the land. Today, grazing systems are primarily found in the more marginal areas which are not well-suited for cropping due to topography, low temperature or low rainfall. Around 4% of the total world population lives in these systems in the developing world (Steinfeld et al., 2006). Based on an analysis of Thornton et. al. (2002), Haan et. al. 2010 (2010) discern two different grazing systems: extensive and intensive grazing systems. In general, the majority of grassland based systems can be found in the developing world.

Characteristics of extensive grazing systems

This group covers most of the dry areas of the tropics and continental climates of Central Asia, North America, Western and Southern Asia and Sub Saharan Africa. Pastoralists dominate in this group, both in the developing and in the developed world. Typical examples are pastoralists in the Sahel zone, extensive meat and milk production systems in Central and

South America (eg. the Andes), the steppe system in Mongolia, transhumant sheep-based systems in Nepal, Pakistan or New Zealand.

Since extensive grassland based systems are mostly found in marginal zones, their importance for global production of livestock products is rather low. These systems provide around 7% of the world's global beef, 12% sheep and goat, and 5% of total milk supply.

Today, these extensive grassland systems are facing several threats, especially the pastoralist systems (Steinfeld et al., 2010; Dong et al., 2011). The main sustainability issues are degradation of rangelands, e.g. overgrazing during the dry season caused by the impossibility to migrate, or the competition with wildlife. Droughts are the main concern for food security, besides the lack of diversification of income sources, and livestock diseases. As pastoralists do only seldom slaughter their livestock, milk is a highly important source for nutrition. However, some scholars note the importance of mixed meat and dairy consumption for an improved ingestion of iron, zinc and vitamins; pastoralists often live at the lower threshold of nutritional energy availability (Galvin, 1992).

Uncertainties about land tenure are often an obstacle for pastoralists to make legal claims for land they are using. The future of pastoralists heavily depends on governments decisions to set conditions for pastoralists to be able to migrate between locations and not to be limited in their mobility by farmers and the conservation lobby (Blench, 2001; Dong et al., 2011). Another option for pastoralists is to commercialize, but this is often associated with environmental and social risks (Davies et al., 2010). Pastoralism is often a possibility to adapt to uncertain environments. As pastoralists are becoming more market oriented, market orientation can consequently reduce the resilience of these systems. However, these effects are not well researched and remain unclear (Davies et al., 2010).

Characteristics of intensive grazing systems

Intensive grazing systems can be found in the temperature climate zones of Europe, North and South America, and increasingly in the humid tropics (eg. Brazil). The main species of this livestock system is cattle (for dairy and beef), relying on high quality grassland fodder. Typical examples for these systems are cattle ranching in the Amazonia region (with Zebu cattle), but also cattle ranching in the United States.

These systems contribute around 17% of the total world beef and veal supply (same share for sheep and goats), and 7% of the global milk supply (Seré et al., 1996).

As most of these systems are in regions with higher income, food security issues are not as virulent as for extensive grazing systems. However, there are some severe environmental concerns, such as competition for highly-productive land with fertile soils (which could produce food crops for direct human consumption), overstocking, or soil degradation due to trampling.

3.2.3. Mixed farming systems

The rainfed mixed farming systems are widespread in the temperate zones of Europe and the Americas, as well as in subhumid zones of topical Africa and Latin America (Steinfeld et al., 2010). Irrigated mixed systems are particularly dominant in East and South East Asia. Typical examples of these systems in the industrial regions are the farming systems of Central and Northern Europe, or the luzerne/maize-based intensive dairy systems in California. In the developing world, mixed crop–livestock farms are found across the semi-arid (also known as dry savanna) region of West Africa, dryland systems in India, as well as farms around the setse belt crossing Central and West Africa, the rice-cattle systems in East Asia, and smallholder systems in the Ethopian Highlands.

Characteristics of mixed rainfed systems (MRT)

The MRT system is found to dominate in two contrasting agro-ecozones of the world: it is the dominant system in most of North America, Europe and North-Eastern Asia; here, it basically covers large strips of land north of 30° northern latitude. It can also be found in the tropical highlands of eastern Africa (e.g. Ethiopia, Burundi, Rwanda) and the Andean region of Latin America (e.g. Ecuador, Mexico; Seré et al., 1996).

MRT is the dominant global livestock production system. Approximately half (53%) of the global milk supply, and a bit less than half (48%) of total beef supply is produced in rainfed mixed systems.

In these regions, the sustainability problems related to agricultural intensification prevail, such as e.g. serious human health hazards trough zoonoses, negative effects of manure concentration or competition for water, notably in arid and semi-arid regions. Issues of food insecurity emerge mostly in the tropical and subtropical regions. Thornton et al. (2002) lists the following threads to food security in these regions: droughts, crop failures, lack of animal assets, poor and declining soil fertility paired with limited access to fertilizers in dry regions, and extreme temperatures and livestock diseases in other regions.

Mixed irrigated systems (MIT)

MIT prevail in dry and humid regions in East and South Asia, mostly in areas with relatively high population density, the Far East, and in developed countries (e.g. in the Mediterranean). Besides meat production, the use of ruminants for draft power is vital for these systems.

MIT contribute about one third of global pork, mutton and milk production and about one fifth of global beef production.

According to Thornton et al. (2002), most households which rely on these systems are food secure. However, in some regions diets depend to a large extent on rice, and thus diet quality is not satisfactory. In arid regions, droughts, the fragility of the environmental equilibria, and subsequent crop failures jeopardize food security. Specific sustainability problems in these systems are concerned with irrigation (loss of soil fertility, competition for water), but also environmental problems that are related to intensification, as for example serious human health hazards, e.g. zoonoses, competition for water, or disposal of manure.

3.3. Biomass flows in the livestock sector

This chapter elaborates on the global scope of the livestock sector. It gives a quantitative overview of the global crop production and the use of crop products as livestock feed, including a breakdown of uses for feed versus uses for direct human consumption. The data are displayed in a breakdown to continental regions as shown in Figure 6.[8]

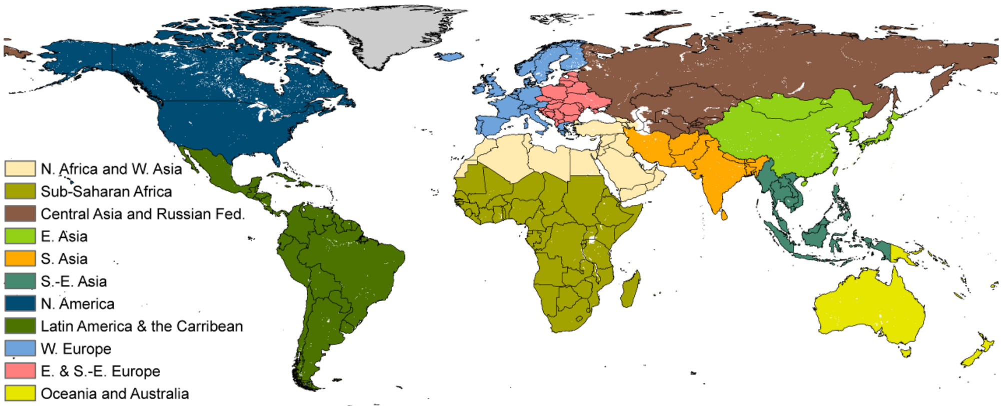


Figure 6. Continental regions used in this study.

The livestock system is a dominant part of the global biomass production and consumption system. Figure 7 displays the composition of global human diets in the year 2000 in kcal/cap/yr. Livestock products play a significant role, but as with 16% of the global overall diets, are small in comparison to other fractions such as cereals (50%) or the sum of all other primary crops (34%). At the regional perspective, however, animal products can reach as much as 37-38% of the overall dietary input (e.g. for the industrial regions North America and Western Europe). In contrast, the share of animal products is as low as 5 -7% in the regions Sub-Saharan Africa and South Asia, respectively.

[8] Most of the data presented in this chapter refer to the year 2000, which is the only year where consistent and comprehensive data on socioeconomic biomass flows (Krausmann et al., 2008), biomass flows in ecosystems (Haberl et al., 2007) and land use (Erb et al., 2007) exist. These datasets are the result of thorough and coherent modelling and computation efforts. Updating these datasets to more current points in time was beyond the scope of this study, due to the massive efforts necessary to produce robust consistent results. These databases are the empirical basis of the model calculations presented in the subsequent chapters. Most of these data are based on the dataset provided by the FAO (FAO, 2011b) and, if not otherwise specified, refer to three year averages for the period 1999 to 2001. Data for the year 2005 are only used when available in a consistent manner.

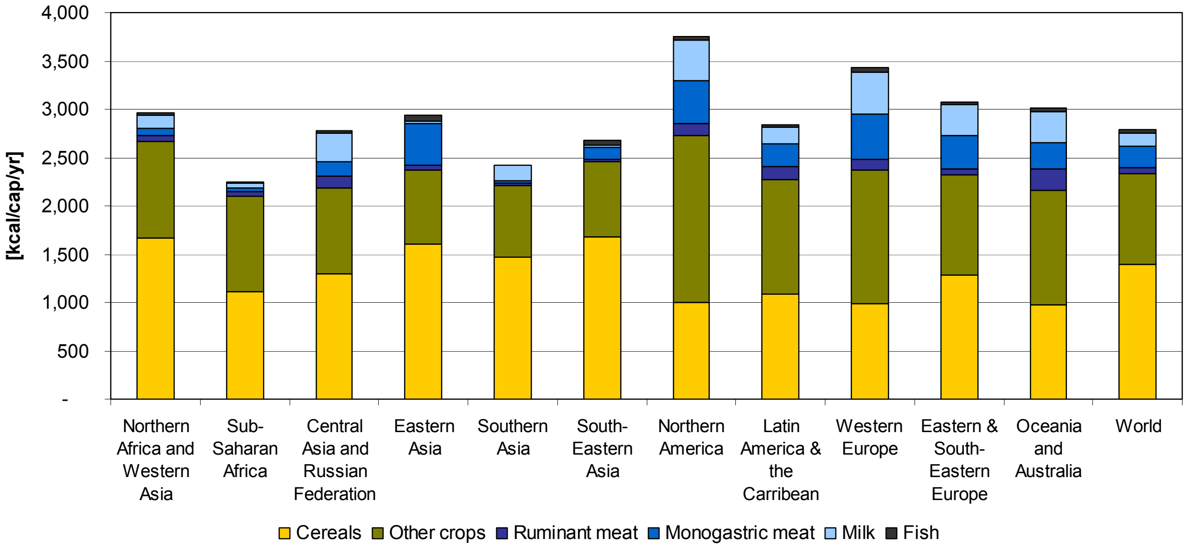


Figure 7. Composition of global per-capita diets in the year 2000, break-down to regions.

Behind these consumption flows are significant global land use areas. Figure 8 displays the amount of cropland and grazing land in the year 2000 according to Erb et al. (2007). In contrast to global diets, animal production dominates global land use areas. Grazing lands amount to more than 45 million km², which is approximately 36% of the global ice-free area (Erb et al., 2007), and spans a huge range of ecosystems, from intensively managed meadows to savannas and semi-deserts. A significant fraction of this grazing land is used as permanent pasture (34 million km²; FAO, 2011b). But all these areas, although sometimes not very productive, are under a certain grazing regimes, often only very extensively. According to area, grazing class 4 (the most marginal or infertile land) dominates by large the picture, followed by the most suitable land (class 1), that encompasses approximately one quarter of global grazing lands. In overall terms, class 1 delivers 63% of the globally grazed biomass (class 2, 3 and 4, 8%, 8% and 20% respectively; Haberl et al., 2007).

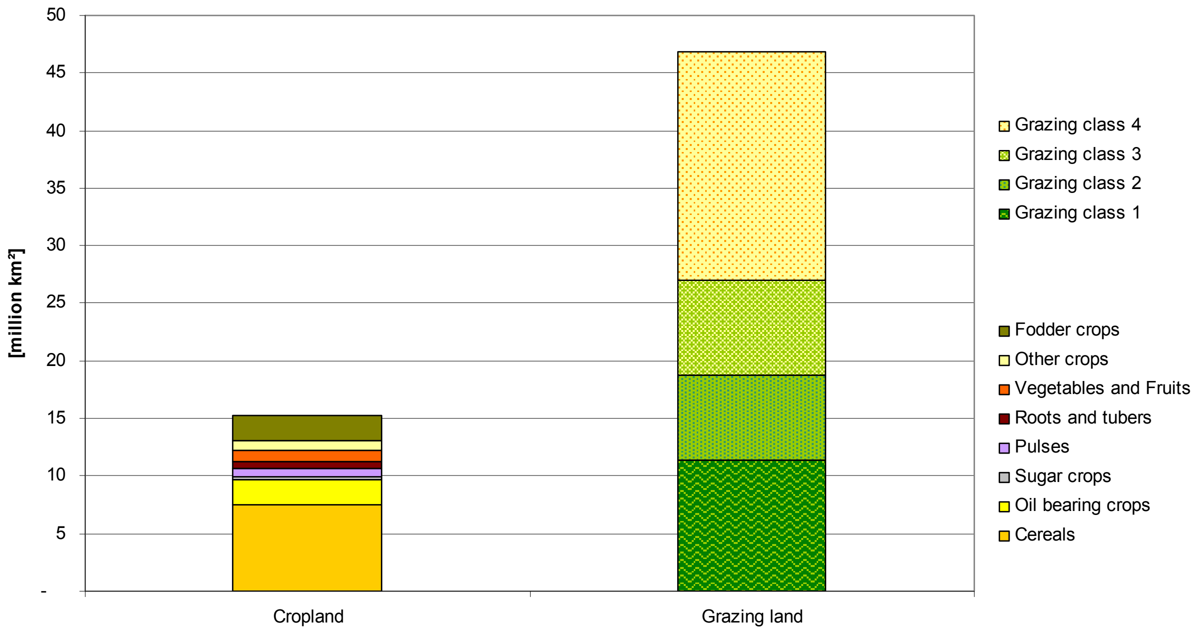


Figure 8. Area under cropland and grazing land in the year 2000. The cropland bar displays the area under different cultivar groups including fallows; approximately 20% of this area is used for feeding livestock (Foley et al., 2011). The grazing land bar shows grazing land according to four grazing land classes; class 1 denotes the best suitable grazing land (managed grazing lands or high fertile grasslands), class 2 denotes high fertile grazing land bearing other landscape elements, such as open forests, class three denotes land with low productivity bearing herbaceous cover or mosaics, and class 4 the least suitable grazing land with sparse vegetation cover, such as semi-deserts. Source: Erb et al., 2007

Additionally, a substantial share of global crop production is fed to livestock. In the year 2000, 15.2 million km² have been under cropland use (Figure 8), a significant fraction producing feedstuff for livestock production (see Table 2). Approximately 3.5 million km², 20% of the global cropland area, were used to produce this feedstuff. Thus, all together, grazing uses around 75 % of world's agricultural land (Foley et al., 2011).

Figure 9 displays a break-down of the output of livestock systems according to the above-discussed livestock classification scheme. For products from monogastric species, landless systems dominate by far the picture. 54% of all monogastric products are produced in land-less systems. For ruminant meat production, only 9% are produced in this livestock system type. For milk production, and less pronounced for ruminant meat production, mixed, rainfed systems of the temperate zone dominate (62% for milk, 34% for ruminant meat). Furthermore, this system is also an important producer of monogastric products (14% of the total). Mixed irrigated system in the tropics are particularly important for monogastric production, whereas this livestock system plays a subordinate role to ruminant production.

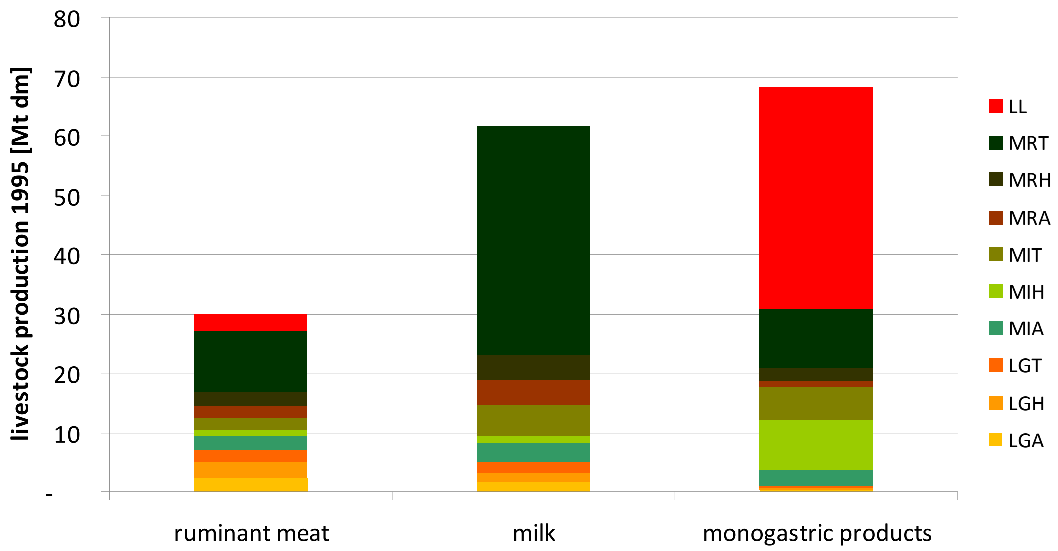


Figure 9. Total output of ruminant and monogastric livestock in 1995, break-down to livestock systems. LL Land-less systems; LG: livestock-based, grazing only; MI: mixed irrigated, MR: Mixed rainfed. A: arid, H: Humid, T: temperate. Source: Seré et al. (1996).

3.3.1. Feed demand of global livestock

Feed supply for livestock consists of market feed and non-market feed. Market feed is comprised of primary crops (such as cereals) and secondary products from processing, such as oil cakes. Market feed supply is documented in the international statistics by FAO (commodity balances). These databases give detailed information on the supply of feed from primary crops and food processing.

Non-market feed from cropland consists of fodder crops such as leguminous crops, maize for silage, fodder beets etc., cropland residues (e.g. straw, leaves) and biomass grazed by livestock or mowed. As the name indicates, non-market feed is usually not traded or transported over longer distances, and is not included in statistical databases. The amount of fodder crops used for feed supply can be estimated on basis of production databases (harvest of fodder crops). An estimate of feedstuff from crop residues (straw, leaves) for each country can be assessed on the basis of factors that indicate the ratio of primary to secondary product and the fraction used for feed (for references see Krausmann et al., 2008). Statistical data do not include comprehensive estimates of biomass grazed by livestock or mowed for livestock sustenance. Modelling techniques have to be applied to estimate the amount of these biomass compartments, such as feed balances: grazed or mowed biomass can be assessed as the difference between (a) feed demand (e.g. calculated by a livestock model) and (b) the supply of market and non-market feed in each country ("grazing gap", Wirsenius, 2003; Bouwman et al., 2005; Krausmann et al., 2008).

Global total feed demand of ruminants (weight of dry matter) is seven times as large as the global feed demand of monogastrics (Figure 101a). The demand for global market feed amounts to 1 Gt dm/yr, in contrast to an overall demand of 5.4 Gt dm/yr of roughage. Nevertheless, market feed is essential for monogastrics, and plays an important role for ruminant livestock systems, in particular in regions where industrialized livestock systems prevail (see Figure 6). Note that the nutritional value of market feed is higher than that of roughage. Market feed can thus substitute for a relatively larger amount of roughage.

Traditional breed ruminants can make use of low grade feedstuffs. Monogastrics, while they are faster growing, are more specialised, and more rapidly producing breeds require feedstuff of higher grades. Figure 10b displays the annual production of meat, milk and eggs in Gtdm/yr.[9] Output is much lower than input, indicating the dimension of energy losses in livestock production. On the global average, 25 units of feedstuff are used to produce one unit of livestock output, if measured in dry matter/yr.

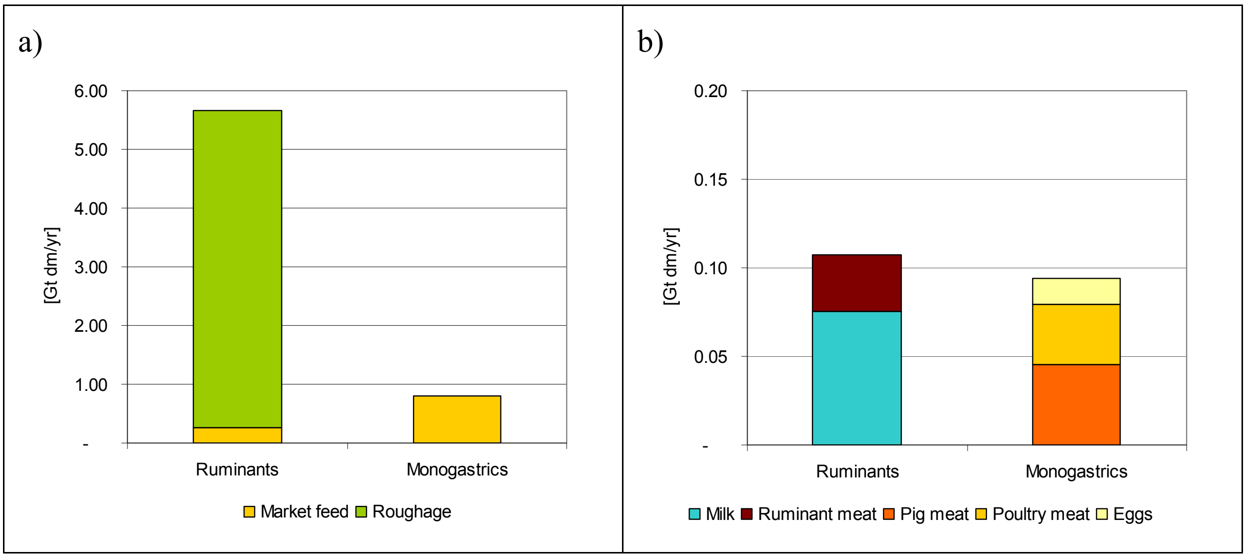


Figure 10. Inputs and outputs of the global livestock systems in the year 2000. a) Feed demand of global livestock in the year 2000, as calculated in Krausmann et al., (2008); b) Production of Milk, Meat and Eggs in the year 2000, source: FAO, 2011b. Note the different scales of the y-axes.

[9] Note that these data refer to the year 2000 and are thus different from the data displayed in Figure 10.

The ratio of roughage to market feed in each region is displayed in Figure 11. Market feed supply is high in regions with a large monogastric population of livestock (e.g. Southern Asia, Western Europe), which are mostly densely populated regions. Roughage dominates the picture in particular in low-density regions such as Latin America or Oceania and Australia.

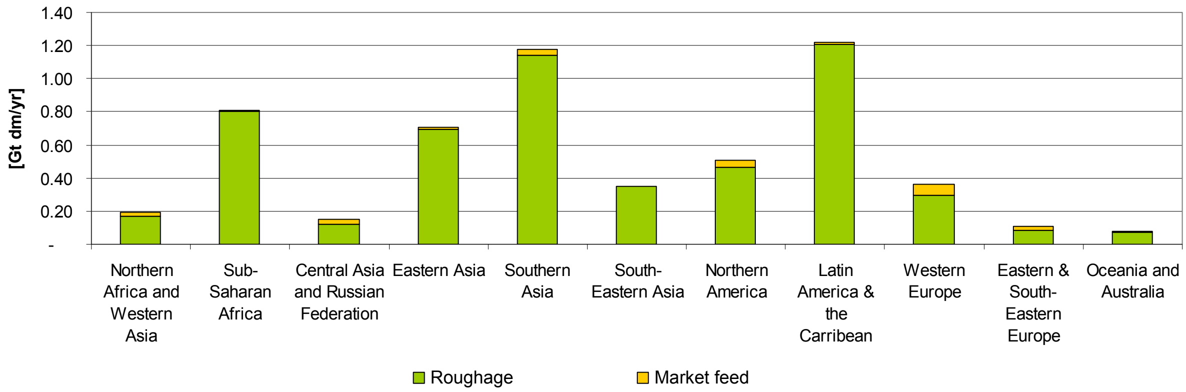


Figure 11. Total feed supply of ruminants in the year 2000, break-down to regions.

3.3.2. Global composition of market feed

As discussed above, livestock is fed with crop products and roughage. While for the latter no direct competition between food and feed exists, crop products typically would be fit for human consumption. This section explores which crop products are used as livestock feed and to what extent they are used to produce animal products. To be able to aggregate different crops, fresh weight data were converted into tons dry matter, using standard factors on water contents of crops (Krausmann et al., 2008).

To set the scene we will first show patterns of global crop production. This is followed by a section which shows how this production is used at the global scale, differentiating uses for food, feed, seed, non-food uses and wastes (the latter refer to losses along the production chain, household level food losses are included in the food category, FAO, 2011b). Regional self-sufficiency rates are calculated to show which regions depend to which extents on imports from other regions. This is followed by a closer look at what shares of crops are used as livestock feed and how much of them are fed to animals in absolute terms. As cereals take a central role in livestock feed we will look into this crop category into more depth before focusing on regional trade patterns in cereals and oil-crops. Finally, country level patterns of cereal self-sufficiency and use for food and feed are presented.

a)

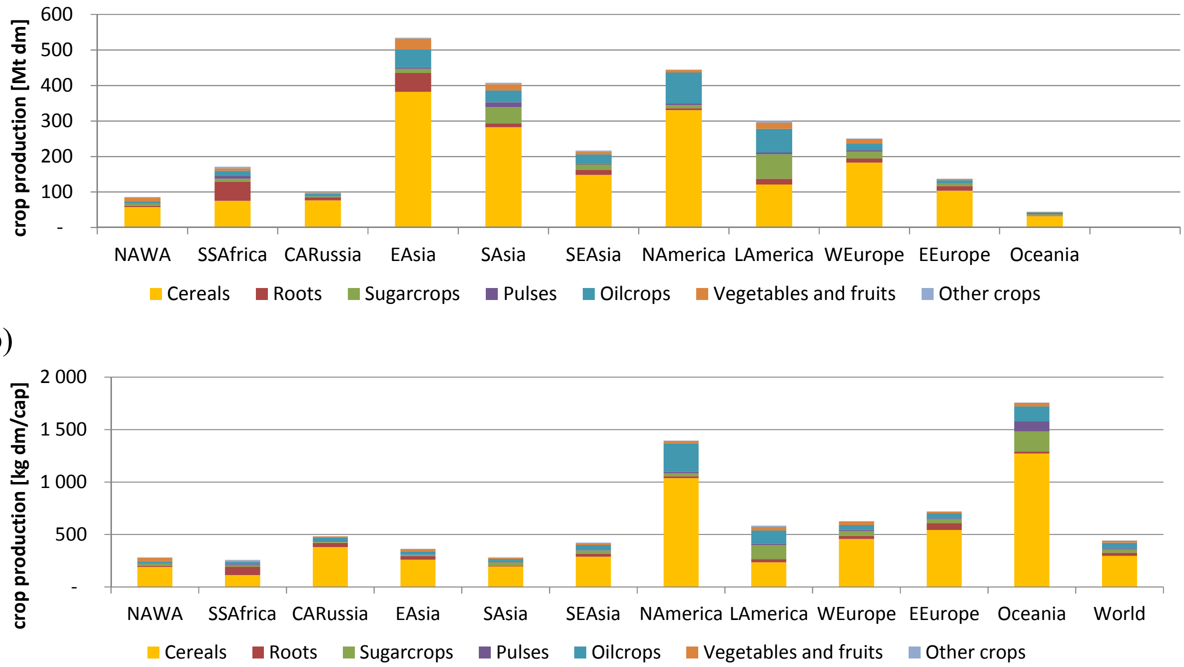


Figure 12. Global crop production in 2000 according to regions and crop categories in a) regional totals and b) per capita values.

Figure 12 shows global levels of crop production in dry matter for the year 2000, in (a break down to) the eleven regions distinguished in this study. The populous regions of Eastern and Southern Asia, along with Northern America show the highest production in absolute terms (12a). Looking at per capita values (12b), however, shows very high levels in Northern America and Oceania, with large regional differences. South Asia and the African regions range at the lower end of the spectrum, North America and Oceania at the higher end. For instance, between Sub-Saharan Africa with just over 200 kg dm/cap/yr and Northern America with 1400 kg dm/cap/yr this difference amounts almost to factor seven. The global average in the year 2000 was just over 400 kg/dm/cap. Figure 12 also reveals the dominance of cereals; they compromise the majority of crop production in all regions with the exception of Sub-Saharan Africa, where roots and tubers are staples, and Latin America, where large amounts of sugar- and oil-crops are grown.

Figure 13 shows the use categories of crops, again for the regional total and in per capita values. The most populous regions also have the highest levels of use in absolute terms, and the consumption is dominated by food and feed use. The per capita values reveal that differences in food use around the globe are small, while differences in crop use per region are largely determined by how much feed is used.

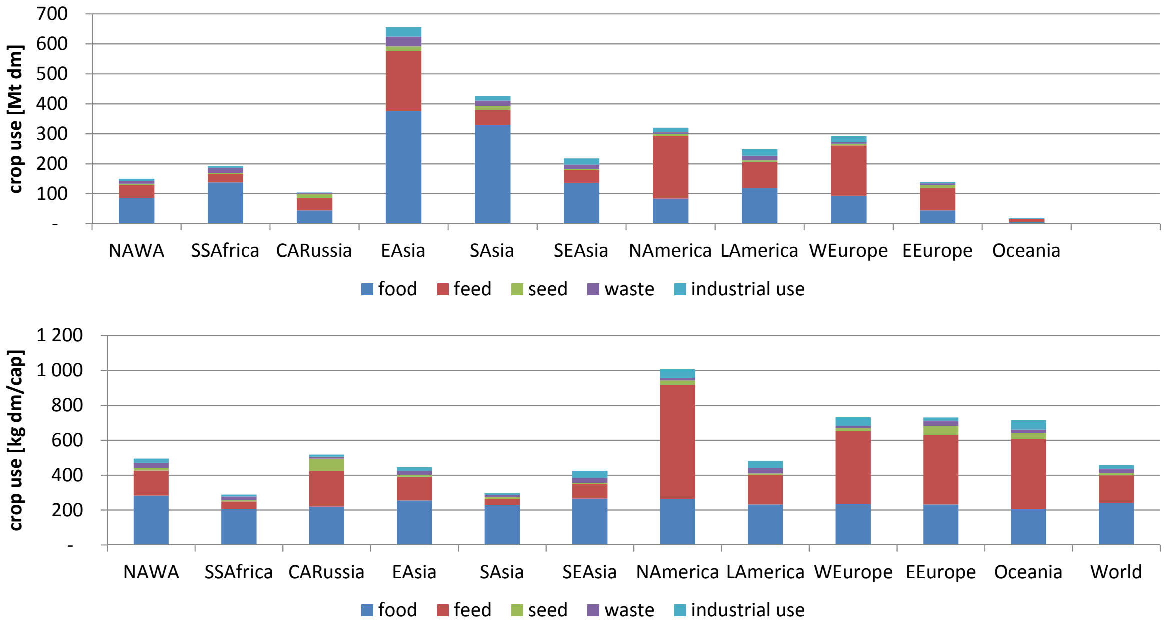


Figure 13. Global crop consumption in 2000 according to regions and type of use; regional totals (above) and per capita values (below); industrial use refers to non-food uses of crops, for instance soap production and biofuel use.

The Figure 13 reveals that in developed regions, the amount of global primary crops used for animal feed is considerably larger than food use. Northern America exhibits levels of per-capita feed use about 2.5 times higher than total per capita crop supply in many developing regions, e.g. Sub-Saharan Africa (about 650 kg dm/cap/yr vs. 260 kg dm/cap/yr). The two European regions as well as Oceania show similar large amounts of cropland produce used as feedstuff.

Table 1 shows to what extent crops of different categories are used as livestock feed. Globally, the highest shares are found in oil-crops[10] and cereals, with 53% and 38%, respectively; also relevant shares of root crops (especially in Eastern Asia, but also in Eastern and Western Europe) and pulses are fed to livestock. Among the animal products it is interesting to see that relatively high shares of fish are used as feed, and milk is needed for rearing calves.[11] Looking at differences among the regions, it becomes evident that the shares in industrialized regions are much higher than the global averages.

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[10] While oil cakes used for livestock feed are typically not fit for human consumption we include them in the same category as crops usable for direct human consumption. This seems justified as the oil-crops could often be consumed as food in other forms and the land needed for their cultivation could also be planted to other food crops with the same levels of inputs.

11 Fish represents an important feedstuff of terrestrial livestock. In 2004, 34.8 million tons (mt/yr) of total fish was used for so-called non-food (i.e. feed produciton) production globally. This is approximately 25% of the 140.5 mt/yr of world total fish produced (FAO, 2007). Another estimation based on these numbers is by Silva and Turchini, who derived that 39 mt/yr of wild catch fish globally are not directly exploited as human food. From this, 16.2 mt/yr (41.7%) are used for livestock feed, which means that 7.1 mt/yr (18.4%) are fed to pigs, 0.3 mt/yr (0.8%) to ruminants and 8.8 mt/yr (22.5%) to poultry (Silva and Turchini, 2008). If more fish was used to cover the livestock's protein demand, the burden on land use changes would be significantly smaller. However, this alternative would bring along or foster the already large problems of overfishing (Swartz et al., 2010). This is important to note, also because the scope of this study does not allow further exploaration of this interlinkage.

Table 1. Shares of crop and livestock categories used as animal feed according to the regions for the year 2000; the values refer to the feed use in total supply.

	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania	World
Cereals	33%	15%	46%	30%	11%	20%	78%	44%	67%	62%	67%	38%
Roots	2%	16%	14%	41%	0%	11%	2%	29%	35%	38%	5%	25%
Sugarcrops	7%	10%	4%	13%	4%	7%	7%	9%	13%	12%	16%	8%
Pulses	16%	9%	68%	41%	8%	13%	27%	1%	72%	57%	84%	24%
Oilcrops	49%	24%	51%	49%	38%	32%	67%	53%	72%	62%	44%	53%
Vegetables and fruits	3%	0%	4%	2%	0%	2%	0%	1%	1%	3%	0%	1%
Other crops	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Meat (ruminants)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Pigs, poultry, eggs	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Milk, butter, dairy	10%	3%	26%	9%	14%	2%	1%	6%	15%	26%	14%	12%
Fish	28%	10%	27%	18%	11%	14%	15%	36%	33%	28%	20%	20%

3.3.3. Feedstuff composition

Figure 14 shows the absolute crop quantities used as livestock feed. In total, a similar amount of feed is used in Northern America and Eastern Asia (about 200 Mt dm/yr), followed by Western Europe. The figure reveals that livestock feed is dominated by two crop categories globally: cereals primarily constitute crop feed around the world, and to a lesser extent oil-crops which are fed in considerable quantities in the form of oilseed cakes and are crucial for the protein supply of the animals. We will now look at the cereal category in more detail and then, to get an idea of the regional interdependencies in these two crop categories, investigate interregional trade patterns.

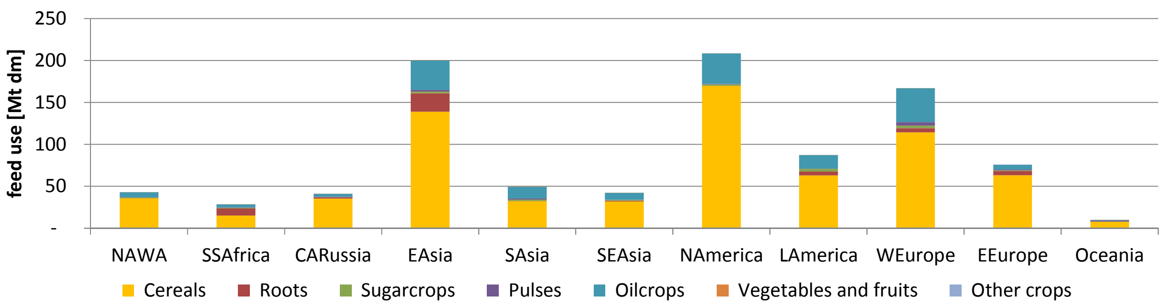

Figure 14. Animal feed use in 2000 according to regions and crop category.

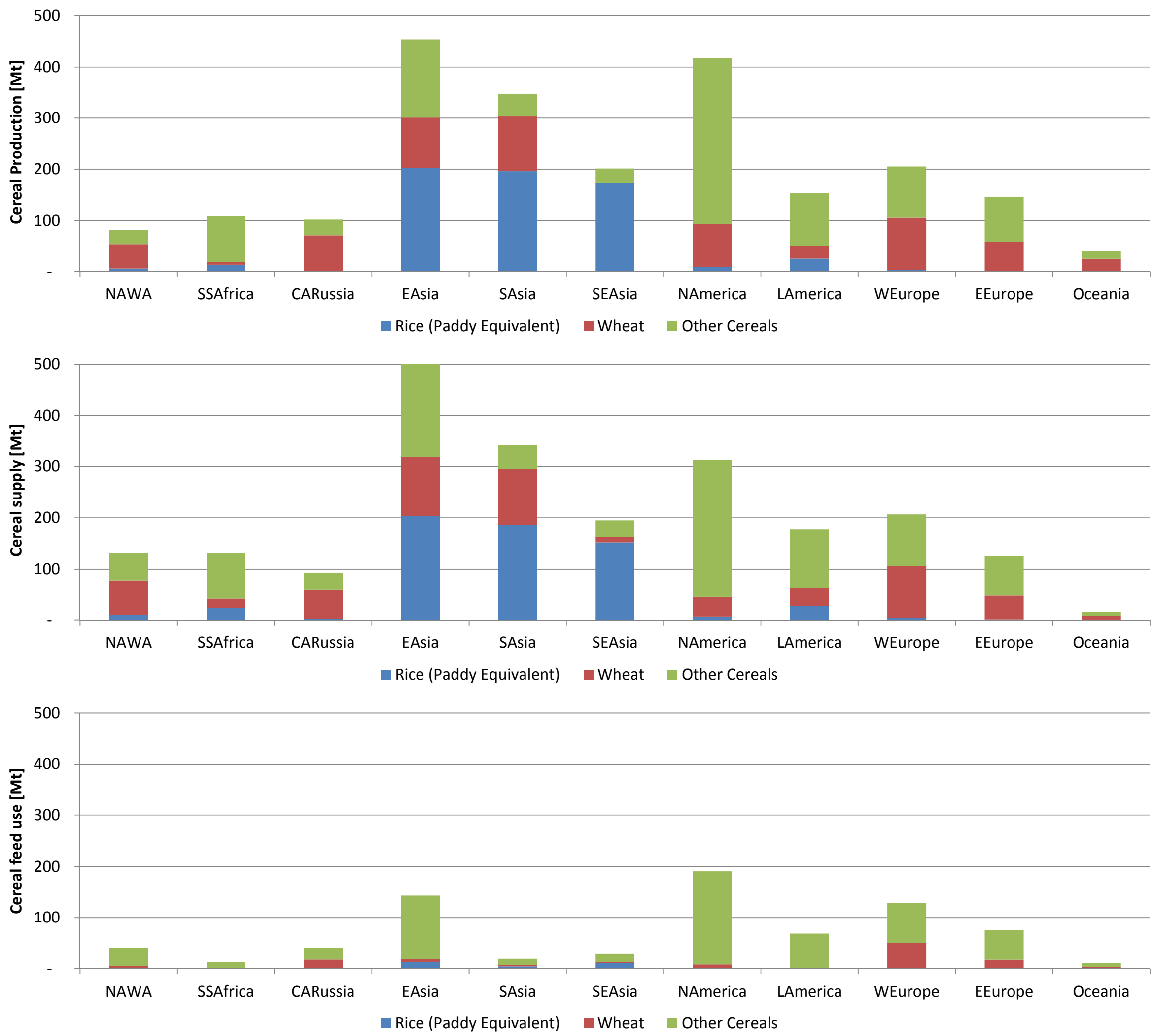

Figure 15. Global cereal production (top), total use (centre, this includes food, feed, seed and industrial uses), direct feed use (bottom) for the year 2005 according to regions; cereals are differentiated into rice, wheat and coarse grains.

Figure 15 shows the global production, use and direct feed use for the global cereal production, differentiating rice, wheat and coarse grains. At the global level, the production of these three categories is within the same range. Rice is dominating the Asian regions, while it plays a minor role elsewhere. Figure 15 also reveals that direct feed use of cereals is dominated by coarse grains (other cereals), in particular maize that plays a dominant role in all regions. Europe is also dominated by the use of wheat for feed. Rice as livestock feed plays a minor role, even in Asia.

Figure 16 displays the ratio of cereals used as direct livestock feed to overall cereal consumption in the regional breakdown. In developed regions almost two thirds of all the available cereals are used for the production of animal products. At the global level, this share is still at around one third, while the lowest shares are found in Southern Asia and Sub-Saharan Africa.

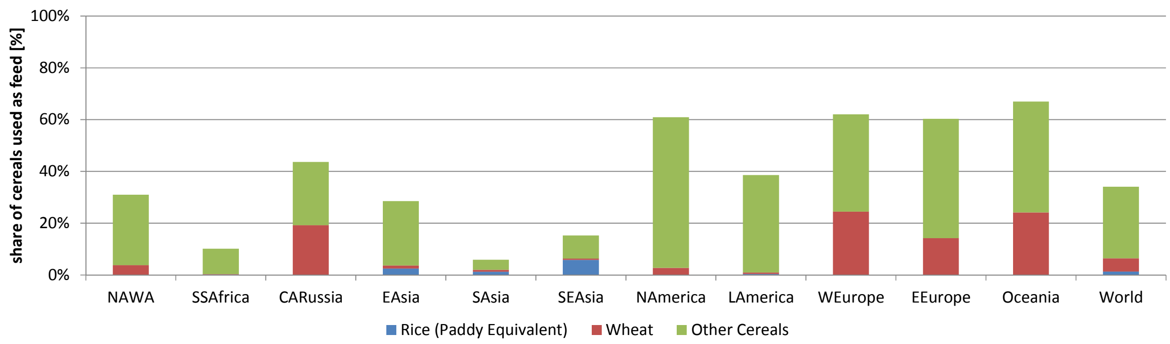

Figure 16. Share of cereal supply used as direct livestock feed for the year 2005 according to regions; cereals are differentiated into rice, wheat and other cereals.

3.3.4. Trade patterns

Trade with biomass products allows regions with high population densities, consumption levels or environmental pressures to gain access to resources or to dislocate production processes to distant territories. International trade shows steep increases in recent decades (Erb et al., 2009b) and leads to increasing interdependency of importing and exporting nations. Increasing import dependency, or lowering self-sufficiency, that can be interpreted as an increased dependency on markets, which, in particular regions with lower economic performance or failing institutions, might result in an increased vulnerability to e.g. price fluctuations (Naylor and Falcon, 2010). We here review quantitative information on the global trade with feedstuff, with particular attention to trade in cereals, the feedstuff closely related to intensification and industrialization of livestock production systems.

Table 2 uses data shown in Figures 15 and 16 to assess regional rates of self-sufficiency for different crop categories and adds livestock products and fish to this picture: Self-sufficiency denotes the ratio of domestic production to domestic consumption, i.e. the fraction of consumption that is produced domestically; self-sufficiency ratios above 1 indicate net-exports, below 1 net-imports.

Table 2. Regional self-sufficiency ratios for crop and livestock categories for the year 2000. The values refer to the ratio consumption to production. Values <1: net importers; >1 net exporters.

	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania
Cereals	0.54	0.75	1.00	0.82	0.96	0.93	1.51	0.86	1.07	1.01	2.76
Roots	0.98	1.02	1.01	0.99	1.00	1.56	1.01	1.00	0.77	1.00	1.04
Sugarcrops	0.53	0.94	0.34	0.72	1.09	1.24	0.34	1.87	0.84	0.76	2.68
Pulses	0.77	0.97	0.98	1.04	0.91	1.34	2.16	0.89	0.71	1.06	1.69
Oilcrops	0.42	0.99	1.00	0.70	0.89	1.01	1.61	2.17	0.33	0.96	1.99
Vegetables and fruits	1.07	1.12	0.81	0.99	1.01	1.10	0.79	1.47	1.03	1.04	1.39
Other crops	0.81	2.74	0.11	0.77	1.19	2.42	0.33	2.09	0.16	0.26	0.25
Meat (ruminants)	0.86	0.99	0.86	0.88	1.04	0.85	0.99	1.05	1.01	1.09	2.53
Pigs, poultry, eggs	0.88	0.90	0.74	0.96	1.00	1.04	1.13	1.02	1.10	1.00	0.98
Milk, butter, dairy	0.82	0.91	0.99	0.86	0.99	0.27	0.98	0.93	1.10	1.08	3.05
Fish	0.81	0.96	1.07	0.84	1.02	1.05	0.80	2.61	0.78	0.50	1.38
total crops	0.58	0.89	0.94	0.83	0.97	1.00	1.40	1.23	0.86	0.99	2.47
total animal products	0.82	0.91	0.90	0.90	0.99	0.94	1.08	1.07	1.04	1.00	2.17
total	0.59	0.89	0.93	0.83	0.97	1.00	1.36	1.20	0.88	0.99	2.41

The difference in production and supply can be explained by interregional trade. Table 2 reveals, for example, that Africa is to a considerable extent depending on imports of crop products. The category "other crops" forms a notable exception. This category contains tropical cash crops such cocoa, coffee and tea, which are exported to a large degree. Regions with the highest degree of self-sufficiency (and therefore net exporters on the world market) are North America and Oceania (although those are also not self sufficient in certain categories). Western Europe is self sufficient in cereals and livestock products, but heavily depends on imports of oil-crops, which are, to a large part, used as livestock feed (see below).

In this section, particular attention will be paid to cereal production, consumption and trade patterns. Cereals (grains) are the one crop category which is crucial for food as well as feed use. For this item, country level patterns of cereal self-sufficiency will be analysed, followed by exploring the relationships between average income levels and rates of cereals use for food and feed. Table listings of the world's major cereal feed users, cereal trading nations and cereal feed importers will conclude this section.

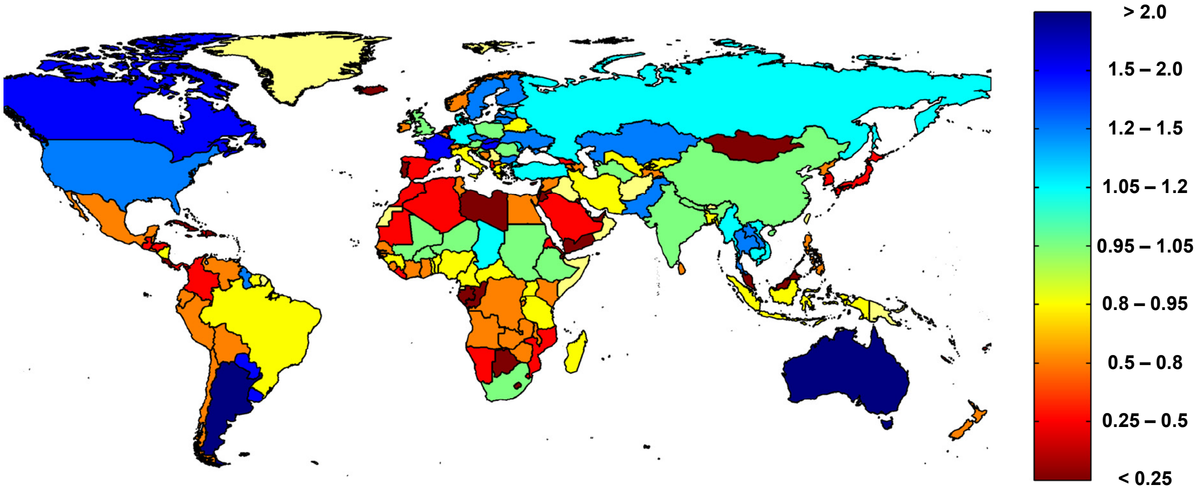

Figure 17. National level rates of cereal sufficiency, calculated as the ratio between total domestic cereal supply to total cereal production. Values below 1 (warm colour gradient) denote net importing countries, Values above 1 (cold colour gradient) denote net exporting nations. A green colour indicates a balance between imports and exports.

Figure 17 presents national level rates of cereal self-sufficiency. North America, Oceania and parts of Latin America produce more cereals than consumed within their territories. African nations as well as nations in Maritime South-Eastern Asia are largely not cereal self-sufficient, in contrast to the countries of continental South-Eastern Asia. At the national level, Europe shows a mixed picture, with a more or less balanced supply and demand of cereals at the continental level (see Table 2). China and India, the world's most populous nations, also show a more or less balanced cereal supply and demand.

Table 3 shows the world's top users of cereals as animal feed. The list is dominated by the USA and China, which together are responsible for 38% of the global cereal use for feed. A number of European nations also show up high on the list, and the 25 countries in the list are responsible for over 80% of global feed use.

Table 3

rank	cereal feed use [Mt]		%	cum%
1	United States of America	168	22%	22%
2	China	115	15%	38%
3	Russian Federation	33	4%	42%
4	Brazil	30	4%	46%
5	Germany	26	4%	50%
6	Canada	23	3%	53%
7	France	22	3%	56%
8	Spain	21	3%	58%
9	Mexico	17	2%	61%
10	Poland	17	2%	63%
11	Japan	16	2%	65%
12	Italy	15	2%	67%
13	Ukraine	14	2%	69%
14	Romania	12	2%	70%
15	Turkey	11	1%	72%
16	United Kingdom	10	1%	73%
17	Australia	10	1%	75%
18	Iran (Islamic Republic of)	10	1%	76%
19	Egypt	9	1%	77%
20	Republic of Korea	7	1%	78%
21	India	7	1%	79%
22	Denmark	7	1%	80%
23	Saudi Arabia	7	1%	81%
24	Serbia and Montenegro	7	1%	82%
25	Argentina	6	1%	83%
	other	131	17%	100%
	total	752		

Table 4

rank	cereal imports [Mt]		%	cum%
1	Japan	27	9%	9%
2	Mexico	18	6%	15%
3	Spain	15	5%	19%
4	China	14	5%	24%
5	Republic of Korea	13	4%	28%
6	Egypt	11	4%	32%
7	Italy	10	3%	35%
8	Saudi Arabia	9	3%	38%
9	Algeria	8	3%	40%
10	Netherlands	8	3%	43%
11	Belgium	8	2%	45%
12	Brazil	7	2%	48%
13	United States of America	7	2%	50%
14	Germany	6	2%	52%
15	Malaysia	6	2%	54%
16	Indonesia	6	2%	56%
17	United Arab Emirates	6	2%	57%
18	Nigeria	5	2%	59%
19	Morocco	5	2%	61%
20	Iran (Islamic Republic of)	5	2%	62%
21	United Kingdom	4	1%	64%
22	Philippines	4	1%	65%
23	Colombia	4	1%	66%
24	Portugal	4	1%	67%
25	Canada	4	1%	69%
	other	98	31%	100%
	total	311		

Table 5

rank	cereal exports [Mt]		%	cum%
1	United States of America	87	27%	27%
2	France	33	10%	37%
3	Argentina	27	8%	46%
4	Canada	20	6%	52%
5	Australia	19	6%	58%
6	Ukraine	13	4%	62%
7	Russian Federation	13	4%	66%
8	Germany	13	4%	69%
9	China	11	3%	73%
10	Thailand	8	2%	75%
11	India	6	2%	77%
12	Viet Nam	5	2%	79%
13	Belgium	5	2%	80%
14	United Kingdom	5	1%	82%
15	Italy	5	1%	83%
16	Hungary	4	1%	84%
17	Turkey	4	1%	86%
18	Pakistan	4	1%	87%
19	Kazakhstan	3	1%	88%
20	South Africa	3	1%	89%
21	Czech Republic	3	1%	89%
22	United Arab Emirates	3	1%	90%
23	Netherlands	2	1%	91%
24	Bulgaria	2	1%	92%
25	Brazil	2	1%	92%
	other	26	8%	100%
	total	323		

Table 6

rank	cereal import for feed [Mt]		%	cum%
1	Japan	11.9	11%	11%
2	Spain	10.8	10%	21%
3	Mexico	6.8	6%	27%
4	Republic of Korea	5.5	5%	32%
5	Saudi Arabia	5.0	5%	36%
6	Italy	4.7	4%	41%
7	China	4.3	4%	44%
8	Netherlands	4.2	4%	48%
9	Brazil	3.7	3%	52%
10	Germany	3.2	3%	55%
11	United States of America	3.1	3%	57%
12	Egypt	3.0	3%	60%
13	Belgium	2.2	2%	62%
14	Israel	2.1	2%	64%
15	Malaysia	2.1	2%	66%
16	Portugal	2.0	2%	68%
17	United Kingdom	1.8	2%	69%
18	Iran (Islamic Republic of)	1.8	2%	71%
19	Algeria	1.5	1%	73%
20	Canada	1.5	1%	74%
21	Colombia	1.4	1%	75%
22	Greece	1.1	1%	76%
23	Jordan	1.0	1%	77%
24	Syrian Arab Republic	1.0	1%	78%
25	Philippines	1.0	1%	79%
	other	23	21%	100%
	total	110		

Tables 3-6. Country rankings according to trade patterns and animal feedstuff use in 2005. Table 3: direct use of cereals as livestock feed;Table 4.: Global imports of cereals; Table 5.: Global exports of cereals; Table 6.: Global imports of cereals for animal feed use. For details see text.

Table 4 shows the major importers of cereals. Japan ranks at the first place, followed by Mexico, Spain, China and South Korea. Also very arid countries such as Egypt and Saudi Arabia show up high on the list. The top 25 nations make up 68% of the global total, indicating that a large number of other nations importing considerable quantities of cereals.

Table 5 lists the major exporters of cereals. Here the USA alone supplies more than a quarter of the total world market, followed by France, Argentina, Canada and Australia. 25 countries supply over 90% of the world market, showing the dominance of a relatively small number of exporting nations. Note that Table 4 and Table 5 show gross trade flows. This explains why countries like Belgium and the Netherlands – net importers of cereals – show up in the top exporter lists. As these countries employ large ports they import and re-export large quantities of cereals.

Table 6 uses data on cereal production, trade and feed use to estimate the amount of cereal imports for the utilization of feed. Due to data limitations, this is calculated by multiplying the amount of cereal imports with the fraction of cereals used for feed at the national level, and can thus serve as a proxy only. The results of this calculation indicate that Japan also takes the top place here, followed by Spain and Mexico. The list contains a large number of European countries that use significant quantities of their cereal imports as livestock feed. The top 25 nations cover almost 80% of the global total. The difference to the picture on overall imports in table 4 can be explained by the fact that many African nations that import cereals (for instance Nigeria) do not, by and large, use them as livestock feed but for direct human consumption.

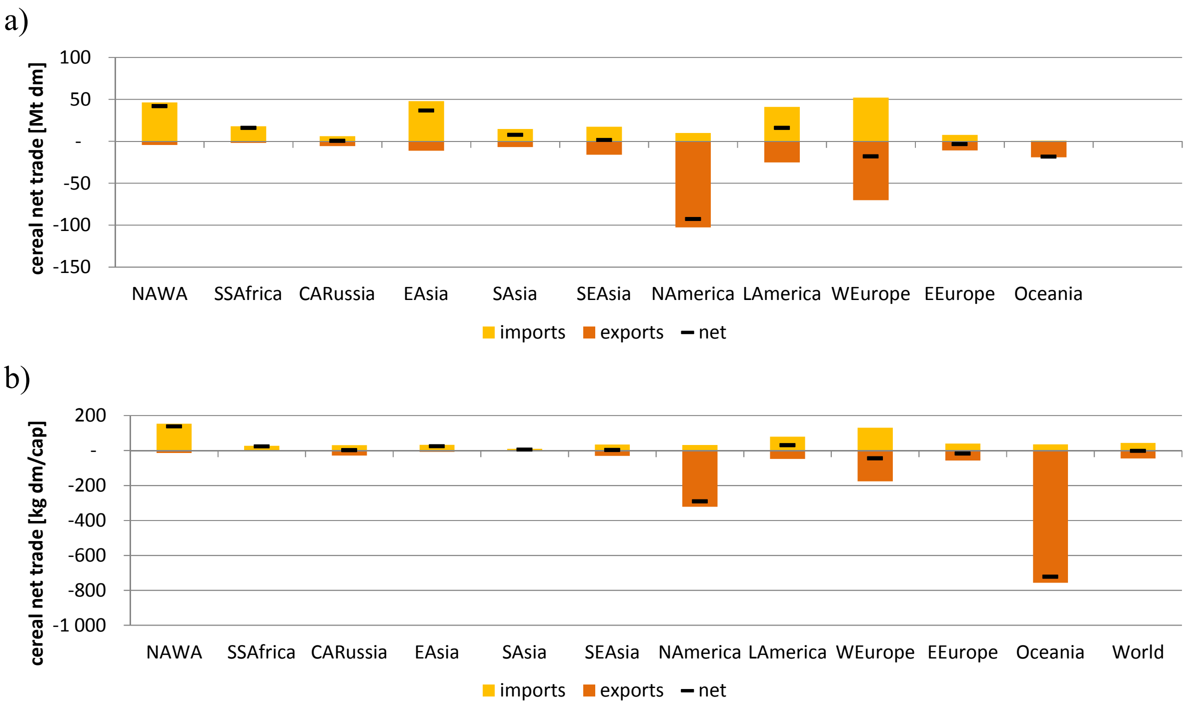

Figure 18. Global cereal trade in 2000 according to regions; a) regional totals and b) per capita values; negative values refer to exports, positive values to imports, the small line indicates the trade balance.

Figure 18 highlights the fact that the world market for cereals is supplied mainly by North America, with Europe and Oceania also making relevant contributions. Eastern Asia and Africa (including Western Asia) are the main regions depending on this supply. The lower part of Figure 18 shows per capita levels of interregional cereal trade and reveals that Oceania and North America export substantial amounts of cereals in per capita terms. Most of the other regions appear rather balanced, with the exception of Northern Africa/Western Asia, which heavily relies on imports. Comparing the global totals of Figures 15 and 18 also reveals that, at the global level, interregional cereal trade plays a relevant role. In 2000, about 15% of global cereal production entered international trade (about 45 kg dm/cap/yr of about 300 kg dm/cap/yr).

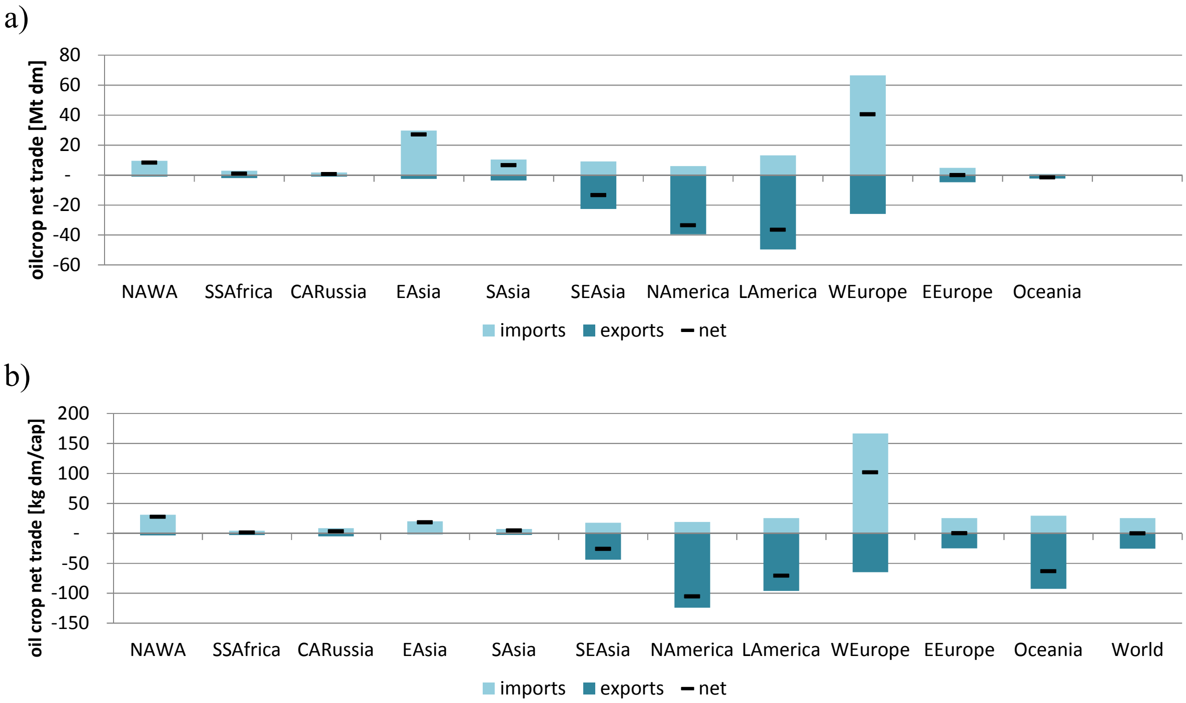

Figure 19. Global oilcrop trade in 2000 according to regions; a) regional totals and b) per capita values; negative values refer to exports, positive values to imports, the small line indicates the trade balance.

Figure 19 complements the picture of grain trade by presenting the interregional trade patterns in oil-crops. This category is dominated by soybeans, oil palm and rapeseed at the global level (these three made up two thirds of global vegetable oil production in the year 2000) and are, next to grains, the next important feedstuff traded internationally. Again, the Americas supply the world market to a large extent, as well as Southeast Asia. Western Europe followed by Eastern Asia present the largest net importers.

The per capita values reveal that at this level imports are dominated by Western Europe, while Oceania also supplies considerable quantities in per capita numbers. At the global level, almost half of the oilcrop production entered international trade in some form (26 of 53 kg dm/cap/yr) highlighting the importance of trade in this category.

3.4. Current trends of the global food and livestock systems

The food system is currently undergoing a drastic transformation that started during the second part of the 20th century. Changes affect and occur in all components of the food system: food production, food utilization, and food access; they also change the role of the food production and consumption system within the socioeconomic system (Ingram et al., 2010).

Global agricultural production has grown considerably over the last century, in particular in the period between WWII and the 1990s (FAO, 2011b). Since then, growth in production has slowed, especially in the developed countries, and per capita production has levelled off in many regions. Food supply is dominated by cereals, oilseeds, sugar and soybeans, and 'secondary' products such as meat and dairy production. With the growth in income, meat, eggs and dairy consumption have grown much faster than crops. This led to changes in the composition of food demand, especially in developing countries. Here, basic cereals and staple food items are replaced by fruits, vegetables, meats and oils, at an accelerating pace (Caballero and Popkin, 2002; Ingram et al., 2010). Rising income and urbanization increase the demand for livestock products and highly processed foods, and decrease demand for staples (Rosegrant et al., 2001). This places additional pressure on land resources through demand for pastures and coarse grains for feed. Such dietary shifts show large regional disparities, but in their sum result in far-reaching alterations for the entire food chain: they transform the structure of production systems, the ways in which consumers obtain their food, and the nature and scope of food-related health and environmental issues facing the world. The reasons for these dietary shifts include income growth, urbanization and the spread of global processing and retail companies (Caballero and Popkin, 2002; Pingali, 2007).

Income plays a central role in these changes. Figure 20 plots national level shares of cereal use for direct human consumption and livestock feed against per capita income levels. While there are considerable deviations, the general trend highlights that nations at low income levels use most of the available cereals directly as food, while the share of cereals used as animal feedstuff is increasing with economic development (e.g. Nonhebel and Kastner, 2011). This "nutrition transition" was found to be closely linked to the level of urbanization within a nation (Caballero and Popkin, 2002).

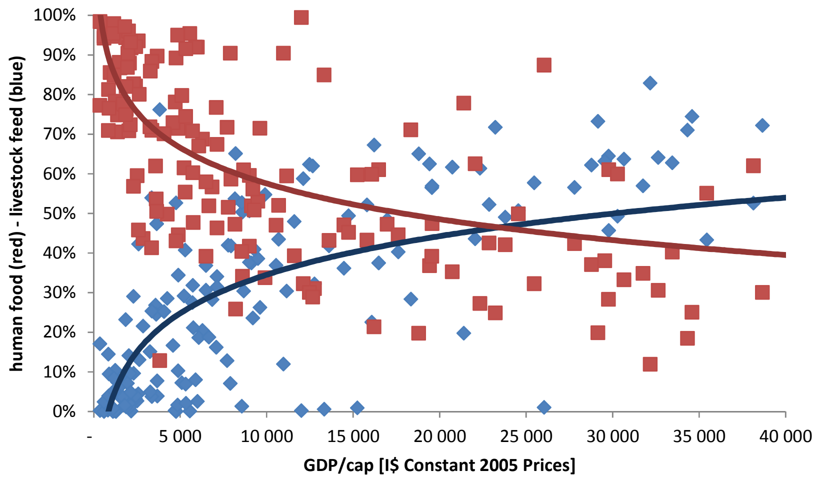

Figure 20. Share of cereals used as human food (red) and livestock feed (blue) at the national level in 2005 plotted against per capita income levels.

Two changes of land use relate to increasing production: land expansion and intensification. In particular the increases in intensity have brought about massive production gains, and in contrast, the expansion of cropland was less pronounced globally (however, it is locally still significant and is connected to ecologically and socially detrimental developments such as deforestation in the Brazilian Amazon). These yield increases show strong regional disparities; in particular in Africa, where smallholder agriculture still underpins food security, agricultural yields are low in many regions. Many scolars identify large potentials to increase yields especially for Sub-Saharan Africa (e.g. also for bioenergy production; Fischer et al., 2001; see Haberl et al., 2010). But as increases in yields rely on the use of inputs such as improved germplasm, fertilizer, labour, pesticides, irrigation and machinery (many of which have become expensive for farmers in recent years as a result of higher energy prices and reduced government subsidies), the realistic potentials to increase yields in the mid-term run is probably much lower than the technological potential (Bruinsma, 2003; Haberl et al., 2010, 2011).

Livestock production has experienced profound technological changes and the vast majority of the recent growth in the production of meat, milk and eggs comes from intensive industrial systems (especially the pig and poultry sector, see Haan et al. in: Steinfeld et al. 2010). Globally, intensification involves a switch from low-input-low-output animal keeping (or mixed farming) to high-input-high-output animal production. Intensive farming is characterized by either raising stocking densities (concentration/crowding - less space allowed per animal) or measures to increase yield per animal. These are: indoor or feedlot housing, concentrate feeding (cereals and oilseeds such as soya), selective breeding and/or a switch to commercial high input breeds. This intensification and industrialisation poses several challenges to animal welfare.

The trend away from extensive and pasture fed towards landless, grain fed livestock systems prevails (Blench, 2001; Bruinsma, 2003; Bouwman et al., 2005; Alexandratos et al., 2006; Steinfeld et al., 2006, 2010; Gerber et al., 2010). This is considered to bring advantages of efficiency in terms of production rates, meaning that the output of the system per unit of time is larger than in other livestock production systems. Furthermore, economies of scale effects lower the cost of production: Broadly speaking, if the quantity of production increases, the average cost of each unit decreases in the long run until the law of diminishing returns sets in[12]. Also, these systems require less input for the production of one unit of output, and are thus more resource efficient in a narrow sense. Nevertheless, as livestock (in particular ruminants, but to a lesser extent also monogastrics) are able to digest biomass not usable for human food, livestock can be seen as a means of harnessing marginal resources, and thus allows to increase the resource basis of society. This function of livestock, however, is more and more placed in the background with the progression of the above-mentioned intensification trends. Moreover, landless, grain-based production systems rely on significant inputs of energy, e.g. for transportation and heating.

The globalization of food systems triggered large growth in international trade of food and feed. For exporting countries, this can be a considerable source of income and therefore allows being competitive in international markets. Furthermore, exporting industries can raise employment and subsequently positively affect food security. On the other hand, importing countries gain access to resources they would not be able to produce at reasonable costs on their domestic territory. However, there is strong indication that this mutual interrelation between importers and exporters is often asymmetrical, i.e. in cases when prices do not take externalities into account, such as in cases in which exporting countries are not fully compensated for the loss in natural resources (Muradian and Martinez-Alier, 2001), or when only specific social groups profit from the exporting industries. Gura (2008), for example, describes the case of the pig sector in Brazil, where smallholders suffer from sanitary regulations, whose high implementation costs prevent smallholders in accessing the new income generation possibilities.

It is predicted that by 2020 the demand for beef, poultry, pork and milk will at least double from 1993 levels (Delgado, 1999). The trend of increasing urbanization all over the world could also create enormous problems for adequate food supply, especially for the growing number of mega-cities (Stamoulis and Zezza, 2003). In the light of these developments, it is anticipated that food insecurity will increasingly become an urban problem, as more than 57% of people in developing countries are expected to live in cities by 2030.

However, 70% to 75% of the poor and food insecure are currently living in rural areas in developing countries (Stamoulis and Zezza, 2003). For the rural poor, two decisive factors play an important role for food supply and food security: The possibility for subsistence food production, and access to markets to buy food they cannot produce themselves. Rising pressure to "modernize" small scale agriculture can lead to rising food insecurity on a local scale, especially in regions where most of staple crops are produced within small scale agricultural structures (e.g. Sawyer, 2008). Poverty and lack of infrastructure are often mechanisms that detain the rural poor from the ability to buy affordable food, despite rising meat production in industrial livestock systems. Furthermore, market liberalization in developing countries such as Thailand, Pakistan, Brazil or Vietnam do favour industrial

[12] The law of diminishing returns holds that at one point in the production process, if one more unit of a certain factor is added, the production rate starts to decline.

production and exert pressure on smallholders (Gura 2008). Finally, people that cannot sustain a living in rural areas migrate into cities and excaberate urban poverty there.

A significant pressure on food production is exerted by ongoing efforts to produce biofuels, in particular in dry regions. Large areas that are thought to be un-used, marginal or degraded are seen as to bear a huge potential for growing draught resistant energy crops. They ignore the fact that these areas are often used by pastoralists for grazing purposes (Young, 1999; Gura, 2008) and that such pro-biofuel agricultural strategies lead to leakage effects such as indirect land use change (Lapola et al., 2010) and land use conflicts, with only modest benefits for rural economies (Fischer et al., 2009) and strong effects on local food security (Erb et al., 2009a; Haberl et al., 2010).

In an industrialized and increasingly globalized world, agriculture lost its position as the primary income generating (or employment providing) activity in food supply chains, in particular in industrialized, but also in developing countries. Nevertheless, many developing countries still do depend upon agriculture for economic growth. Processes of economic globalization have connected commodity markets and food security outcomes across geographies and over time (von Braun and Diaz-Bonilla, 2008; Erb et al., 2009b; Friis and Reenberg, 2010). Much more agricultural produce is traded than 30 years ago. Food-price shocks in one country or region have ripple effects elsewhere (Ingram et al., 2010).

4. The interrelation between livestock systems and food security

Besides its central role as a source of energy and nutrients, livestock systems fulfil several functions for society, and therefore directly as well as indirectly relate to food security. In particular in agrarian societies, the importance of livestock reaches far beyond its role in nutrition (Sansoucy, 1995; Fresco and Steinfeld, 1998; Dijkman et al., 2000; Blench, 2001; Bruinsma, 2003; Steinfeld et al., 2010; Swanepoel, 2010), and many of these functions indirectly relate to food security. Livestock and crop production interact in both positive and negative ways. Livestock supports crop production through draught power and manure for fertilizer, soil structure and to retain moisture or use as fuel. Animals are re-cyclers of wastes and can graze or browse marginal lands which may be of no other food security value. They help to stabilize food supply over the season and years, in times of shortage, and they provide a significant source of income and store of wealth for smallholders, thereby indirectly providing access to food (Fresco and Steinfeld, 1998; FAO and APHCA, 2002; Bruinsma, 2003). Competing situations arise when livestock consume grains and other cropland products that could otherwise serve directly as human food (FAO, 2011a), as well as water. Box 1 summarizes the functions of livestock in the context of food security. Box 2 lists negative aspects of livestock for food security.

The livestock system can be seen as a very complex subsystem of the biomass production-consumption system. In order to understand it in detail, it is important to focus on the inter-linkages (e.g. material and energy flows) between the different compartments of the system. In this section, we will discuss mechanisms that accompany changes of the livestock system and explore possible implications for local and regional food security.

BOX 1– The role of livestock for food security (based on Sansoucy et al., 1995; Fresco and Steinfeld, 1998; Dijkman et al., 2000; FAO and APHCA, 2002; Bruinsma, 2003; Gliessman, 2007; McIntyre et al., 2009; Gerber et al., 2010; Steinfeld et al., 2010, Gura 2008)

The direct role of livestock for food security

- food source: energy, protein, nutrients
- source of income and employment
- status of the farmer
- store of wealth (hedge against inflation) and form of risk assurance in crop livestock systems (livestock as a buffer)
- broadened resource base: livestock allows to recycle secondary products, household and industrial wastes, and allows for the utilization of marginal lands and crop residues by livestock

The indirect role of livestock

Livestock as a supplier of production inputs for agriculture

- Livestock as a source of energy, e.g. draft power, dung for fuel, biogas
- Livestock as a source of fertilizer and soil conditioner
- Livestock and weed control

Non-food attributes of livestock as a factor of sustainable agriculture

- Increasing animal production saves foreign exchange
- Livestock for investment and savings
- Manure, hair, bones, fur and leather for buildings, clothes, tools
- Social and cultural significance, which may be the main reason for keeping animals in many societies. It is not always possible to attach monetary value to many of these roles. Nevertheless, they cannot be ignored, since animals for cultural or religious events may command very high prices.

BOX 2: Negative aspects of livestock for food security (source: Zinsstag, 2001; Naylor et al., 2005; Steinfeld et al., 2006, 2010; Otte et al., 2007; Bonfoh et al., 2010)

- Livestock compete with humans for crops and therefore for agricultural land
- Livestock consume fish which could otherwise form food for humans or not be harvested and allow fish stocks and marine ecosystems to recover.
- Higher need for resources, such as energy inputs, NPK, land area and water, than crops per energetic output
- Production of livestock products can have a disproportionately high impact on the environment, through soil erosion, pollution to soil, land, water, air and climate, through habitat destruction and species loss
- Large share of animal fats and proteins increase the risk of diseases such as some cancers and heart disease
- Health threats for humans stemming from zoonotic diseases, food safety hazards from infectious agents, antibiotic resistance in humans resulting from incorrect use of antibiotics
- Intensive livestock keeping is often associated with animal welfare issues
- Livestock products are relatively costly to the consumer and may displace consumption of balanced and healthy plant based foods
- Livestock products have a shorter shelf life, particularly in warm climates.
- Measures to reduce disease spread in intensive farming may disproportionately impact small scale and extensive farmers where applied across the board.

4.1. Mechanisms and systemic interrelations between livestock (change) and food security

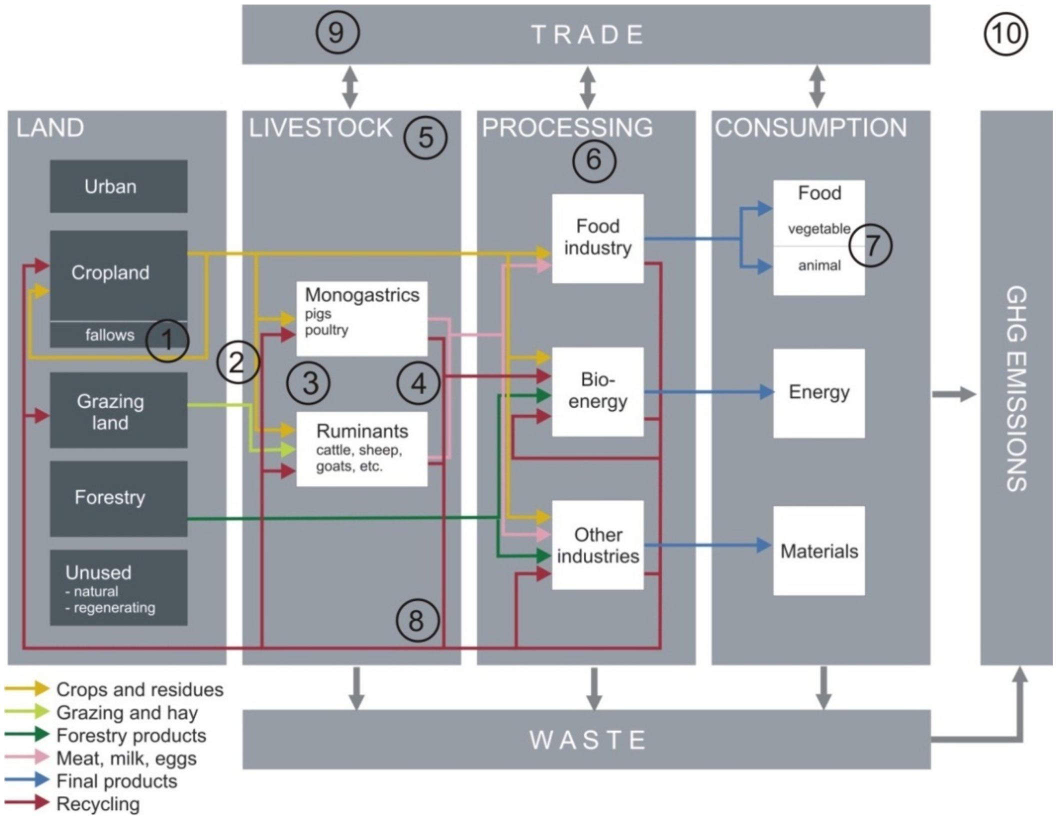

Figure 21. Important mechanisms and systemic interrelations between livestock and food security.
1. Competing land uses, yield increases vs. agricultural expansion. 2. Altered input/output relations: Breeding & GMO. 3. Change in livestock mix: from ruminants to monogastric species. 4. Animal diseases/health risks for humans. Close links to animal welfare. 5. Loss of the multi-functionality of livestock (risk avoidance, draft power, capital stock, etc.). 6. Resource conflicts: agricultural production for food/feed/energy. 7. Impact on human health – overconsumption, malnutrition. 8. Use of waste flows/residues vs. primary products. 9. Land-less systems reduced self-sufficiency vs. availability of (cheap) food. 10. Reduction of (subsistence) livestock herding- opportunities for non-agricultural employment/income.

Figure 21 pinpoints the location of mechanisms underlying the interrelation of livestock (change) and food security within our framework of biomass production-consumption systems. Distributional issues that relate to one of the central aspects of food security, i.e. food access, are effective over the full range of these mechanisms, and are not discussed in detail here. In general, it is mainly the poor that are vulnerable to decreases in food security, as they have limited options and restricted access to factors such as land (tenure), income, and economic opportunities.

1. **Competing land uses.** Industrial livestock systems with their higher share of monogastrics and the higher amount of cropland products (in particular cereals, oil seeds, pulses, roots, most of them also directly utilizable for food purposes) fed to ruminants, will increase the amount of primary crops needed to produce animal

products. This might increase the demand for high quality land, when not achieved by crop yield gains, result in land use competition with other food production, or with cropland expansion at the expense of grazing land or forests. Such developments may push back pastoralists or subsistence agriculture further onto less fertile land, making their often meagre existences even harder (Steinfeld et al., 2006, 2010; McIntyre et al., 2009; Steinfeld and Gerber, 2010; Bouwman et al., 2011; Gilbert, 2011).

2. **Altered input-output ratios.** Livestock breeding is a method used to decrease the amount of feed input per product output. However, Smil (2002) found that, with the exception of poultry meat, efficiency gains have been marginal in the course of the last century. This can partly be explained by the fact that breeders select for more lean meat, which is energetically more demanding to produce (Smil, 2002). The observed (considerable) efficiency gains of livestock systems result, to a large extent, from a switch to high-quality feed which could otherwise feed people (market feed instead of roughage). For smallholders, the benefits of animal breeding or genetic engineering will be limited, because the most important criterion for livestock production in subsistence systems is not the optimal use of high quality feed, but rather the ability of livestock to thrive on residues and waste and thus to broaden the resource base of society (Sansoucy et al., 1995).

3. **Change in livestock mix.** The rapid increase of monogastric species and much slower growth in demand for ruminant products is a central element of the currently ongoing industrialization of animal production. Monogastric species show an increased input-output efficiency over ruminant species, but require feedstuff of a higher quality, especially true when monogastrics are kept in industrial systems. This trajectory closely links to changes in land demand described under point 1. As industrial livestock rearing requires considerable capital, this market may be difficult to occupy by smallholders (Bruinsma, 2003). Furthermore, monogastric species are less suitable for the lifestyle of pastoralists.

4. **Animal diseases-health risks.** Industrial systems tend to keep large numbers of livestock in small spaces. This increases the risk of animal diseases and pest outbreaks, with impacts on animal welfare and human health (Steinfeld et al., 2010; Gilbert, 2011; Liebenehm et al., 2011). If large populations of animals are affected, such outbreaks can also affect regional supply of animal products and thus food security. The fact that, in developing nations, humans often live in close contact with livestock poses the risk of transferring animal pathogens to humans (Blench, 2001; Thornton et al., 2002). Additionally, with the change to industrial livestock production, conditions of animal welfare typically decline. Securing adequate food supply for major parts of the population will be a precondition for the public to take interest in this issue and for actions to improve animal welfare conditions.

5. **Loss of multifunctionality**. With the change to intensive grain-fed, or even landless livestock systems, the multifunctional role of livestock (food, energy provision, draft power, manure, risk reduction) in many rural societies declines (Dijkman et al., 2000; Blench, 2001; McIntyre et al., 2009; Gerber et al., 2010; Swanepoel, 2010). The role

of animals switches to a mere provisioning function of food. Such a switch will depend on industrial technologies and replace labour, resulting in declines of employment and income, and under certain conditions, trigger urbanization.

6. **Resource use conflicts.** In subsistence crop-livestock systems, the farmers can decide to what degree they direct agricultural output to uses for food, feed and energy. With specialized, industrial systems, overall efficiencies may increase, but the focus on food production impacts upon other functions of the livestock systems (e.g. draft power). Also, different uses of biomass are in a potential conflict, most prominently between food, feed and energy. Surges in bioenergy production and grain fed livestock systems from dedicated crops put pressures on land availability and thus on people that depend on cheap world market supply of cereals for food and feed. Important issues that relate to these effects are “indirect land use change” and “land grabbing”.

7. **Livestock products and human health.** The availability and affordability of large amounts of animal products has led to patterns of overconsumption in many, especially developed, nations, causing health risks such as increased obesity and coronary diseases (Caballero and Popkin, 2002). Overconsumption and malnutrition occur often simultaneously. It has been suggested that reducing animal based products in the overall diet, to levels recommended by nutritionists will be beneficial for health as wells as for environmental systems (McMichael et al., 2007; Swanepoel, 2010). Allowing the poor to converge towards adequate and safe consumption levels would also improve their nutritional situation considerably. Moving towards such goals would, however, imply massive interventions into markets, to address distributional issues, and into personal consumer food choices.

8. **Residues, wastes and manure.** Industrial livestock systems require high-quality feed, in many cases crops that could be used also for food. Livestock can, to a certain extent, be fed not only from primary cropland products, but also biomass categories which are of much lower nutritional quality. Wastes and residues accrue on cropland (i.e. straw) and from biomass processing (e.g. brewer grains). With industrialization, the re-use of waste flows and residues might decline, reducing the overall efficiency of the system (Fischer Günther et al., n.d.; Taheripour et al., 2009).

   Nutrient flows that are closely managed in mixed systems can be broken up (Naylor et al., 2005; Bouwman et al., 2011), leading to impoverishment in supplying regions (e.g. the Brazilian Cerrado) and waste problems in consuming regions (e.g in China, Vietnam and Thailand along the South China Sea). Furthermore, manure flows that are used to replenish soil fertility in mixed systems are now spatially separated from cropland and may be harder to obtain for poor farmers: if these farmers own the livestock, they also own the manure; if crop and livestock farming are separated, market feed and fertilizers have to be purchased.

   Excess concentration of manure often leads to environmental problems such as water or air pollution. On the other hand, these flows of manure are lost to the (distant) croplands which in consequence require large amounts of mineral fertilizers to sustain soil fertility and allow for high crop yields. Limited resources (e.g. Phosphorus) or high energy requirements to produce nitrogen fertilizer necessitate a reconsideration of policies aiming at a re-coupling of livestock and land systems in producer countries (Naylor et al., 2005).

9. **Shift towards landless livestock systems.** The trend towards industrial livestock systems and the spatial and economic separation of crop and livestock production offers the advantage for regions with high population densities and environmental pressures to dislocate certain impacts to distant regions (Galloway et al., 2007) and to gain access to affordable animal products. On the other hand, this trend entails a lower self-sufficiency that can be interpreted as an increased dependency on markets. This can in turn increase the vulnerability in particular of importing regions with lower economic performance, e.g. to price fluctuations or price shocks (Naylor and Falcon, 2010). Prices surges will particularly affect the food security of the urban poor in regions who are heavily depending on (international) trade for livestock production (Naylor et al., 2005).

10. **Marginalization of smallholders and pastoralists.** The trend towards industrial livestock systems may occur at the expense of diminishing the market opportunities and competitiveness of small rural producers. Local farmers cannot compete with the low prices of industrialized systems. Additionally, smallholder's access to subsidies might be limited. In consequence, smallholders cost of production is higher than the price they can charge for their goods. Similarly, strict food safety regulations, often accompanying industrial production (see point 4) to enhance public health, constitute barriers that often prevent poor farmers from entering formal markets because they are financially not capable of attaining these cost-intensive certificates (Bruinsma, 2003).

    Intensification of livestock systems is also discussed as a factor in pushing pastoralists further onto less fertile land (see point 1.; Gura, 2008; Dong et al., 2011). This (a) endangers their traditional lifestyle, and (b) renders it important to offer alternatives for employment and income, because marginal land does not provide resources in sufficient quality and quantity. Pressures on pastoralists arise from unclear land tenure, the construction of infrastructure or large farms with fencing, preventing migration with livestock and therefore exclude these groups from access to free goods such as resources and water. Migration of pastoralists into marginal lands can impact on biodiversity, resulting in ecological degradation and a social stigmatization of pastoralists.

5. Quantitative exploration

This chapter is dedicated to the quantitative exploration of the framework conditions influencing the interrelations between livestock systems, dietary requirements and agricultural technology as well as their changes, at the global and continental scale. Basis of this assessment is the biomass balance model developed in a previous project (Erb et al., 2009a).

The biomass balance model, operating at the level of 11 world regions, allows studying the systematic interrelation of different trajectories in diets, livestock developments, yields and cropland expansion, with the aim to derive insights on the option space for future developments. This model was used and extended in order to allow for empirical insights into the interrelation of changes in livestock (systems) and food availability at the global and regional scale.

The model is extensively discussed in the available literature (Erb et al., 2009a; Haberl et al., 2010, 2011). Here, we only shortly outline the model structure, and discuss the modulations of the scenario assumptions

5.1. The biomass-balance model

5.1.1. Spatial resolution

The model operates on the level of the 11 world regions (see Figure 6). Model calculations are performed at this level of regions, without considering any further sub-regional details. This is important to note, as individual countries do not necessarily follow the average characteristics of their regions.

5.1.2. Basis data

The model draws from highly detailed consistent biophysical databases on global socioeconomic biomass flows, land use and the human appropriation of net primary production (HANPP) available for the year 2000 (Erb et al., 2007; Haberl et al., 2007; Krausmann et al., 2008). These databases fulfil multiple consistency criteria across scales and domains. Biomass flows are traced from the net primary production (NPP) of each land-use class to national-level data on final biomass consumption. Spatial scales range from high-resolution datasets (available at 5' geographic resolution, i.e. about 10×10 km at the equator, covering ~98 percent of the earth's land excluding Antarctica) to the country level (~160 countries) and the level of the above-described eleven world regions.

5.1.3. The balancing procedure

On the basis of these datasets, a biophysical biomass-balance model that consistently matches global land demand for biomass products (food, feed, fibres) with gross agricultural production and land use in the year 2000 was developed (Figure 22). Data for the year 2000 were used to derive factors and to set up the architecture of the model. For the scenario analysis, for each compartment of the model different scenario assumptions were derived, in order to compile the supply-demand ratio for each scenario combination.

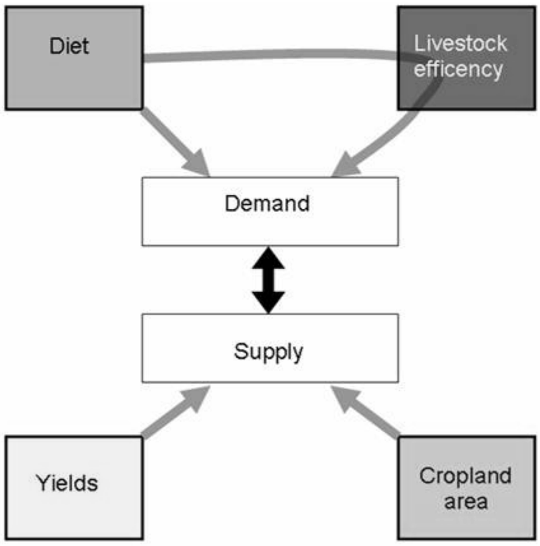

Figure 22. Schematic representation of the architecture of the biomass balance model, used to assess changes in agricultural systems and their consequences for food availability for world regions in 2050. Livestock efficiency refers to input-output ratios of the regional mix of livestock systems.

The biomass-balance model calculates the demand and supply ratio of cropland in 2050 at the global scale. Regional discrepancies of production and consumption of biomass are assumed to be compensated through trade in the biophysical balance model. Scenarios in which global cropland area demand exceeds global cropland availability by more than 5% are labelled as 'non-feasible' (food first approach). A difference of 5% is assumed to be not significant given the uncertainties in the biomass balance model. For grazing demand and supply, we calculated the grazing intensity resulting from all scenarios. Current grazing intensity is found to be at 18% harvest of NPP (net primary production) on grazing land. We assumed a grazing intensity below 25% to be feasible, between 25% and 39% to be probably feasible, and above 39% not feasible. The latter value is derived by calculating the weighted global average maximum, (assuming maximum grazing intensities for the grazing land classes 1 to 4 by Erb et al., 2007of 75%, 55%, 35% and 20%). .

5.1.3.1. The livestock module in the model

The model discerns a food crop path and a ruminant path. Monogastric animal species (pigs, poultry) are dealt as part of the food crop path, because they are assumed to be fed exclusively from primary or secondary cropland products. For the demand for final products, i.e. pig meat, poultry, eggs, and fish from aquaculture, the market feed requirement is calculated by applying regional input-output ratios of the monogastric livestock systems (derived from Wirsenius, 2000; Krausmann et al., 2008). The amount of market feed demand of the monogastric livestock is added to the ruminant market feed demand calculated in the roughage path (see below), resulting in the total regional market feed demand. This is then balanced with the regional supply of market feed from food processing and industrial processing of cereals, oil-bearing crops, and sugar crops, that is, the supply of brans, oil-cakes, molasses and bagasse (by-products of sugar production). Usage factors for these categories from the database in Krausmann et al. (2008) are used to calculate the amount of market feed fed to animals. From the difference between total market feed demand and the amount of by-products from processing fed to animals, the amount of feed grain (cereals) used as feed is calculated and added to the regional demand for cereal crops, taking into account seed demand and losses.

Ruminant meat and milk consumption and production are assessed in a second pathway. The grazing livestock system is characterized by a demand for market feed (e.g. cereals, brans, oil-cakes) and a demand for non-market feed (roughage demand, i.e. the sum of fodder, crop residues fed to grazers, and the amount of grazing). Market feed demand was dealt with in the same manner as with monogastric feed demand. Non-market feed demand is calculated as a function of meat and milk consumption, on basis of regional input-output ratios of the different ruminant systems, taken from Krausmann et al. (2008).

The model can also compute additional land demand for roaming, assuming minimum area standards for pigs and poultry (for details see Erb et al., 2009a) for e.g. humane or organic livestock systems. Such additional area demand is, however, not calculated for cattle, as cattle require a certain amount of grazing land for roughage on which the animals may also roam (at least potentially). As intensive monogastric livestock production is mostly located in intensive cropland areas, we assume that this area reduces the available cropland area in the respective scenarios.

5.2. Scenario assumptions for 2050

Modulations in four dimensions were performed in the scenario analysis: diets, share of animal products (ruminant/monogastrics), livestock effieciency/diets and agricultural yields. For each dimension, a baseline scenario was derived from the literature, which was then modulated in order to explore the option space of the option space in 2050. In overall terms, this resulted in 4 modulations of human per-capita diets and 3 modulations on the composition of animal products within this diet on the consumption side. On the production side, 4 modulations were calculated for agricultural yield levels and 3 for livestock diets/efficiencies.

For all model runs the amount of cropland in 2050 was not varied, and the FAO projections for cropland were used (Bruinsma, 2003; Alexandratos et al., 2006; Erb et al., 2009a): the values of assumed cropland area for 2050 per region are displayed in Table 7. In this scenario, in line with Erb et al., 2009a, cropland expansion was assumed to occur on former grazing land only, and not result in deforestation. Also, we did not assume that grazing land is expanded to forested land; increases in the demand for grazing have been assumed to increase grazing intensity, i.e. the ratio of annually harvested biomass to annual production of grazing lands.

The assumption of only one cropland expansion scenario was motivated by the necessity to keep the number of scenarios within reasonable boundaries, but has important consequences of the interpretation of the obtained results: Scenarios that are found to be not feasible can be interpreted as non-feasible on this cropland area only, and do not imply that further cropland expansion would not be probable or possible in the light of the assumed changes in drivers of land use change (such as e.g. dietary changes). Increasing cropland beyond the assumed values will, in general, enhance the options space on cropland, while at the same time increasing pressures on other land resources, in particular grazing land (or forests). Less cropland expansion or cropland contraction will decrease the option space on cropland, accordingly. However, with regard to findings related to the trade-offs within the livestock sector and between livestock and food security - that are at the heart of this report - the main findings, will, however, remain the same, irrespective of the assumed cropland area expansion.

Table 7: Assumed cropland change for 2050 according to 11 world regions; for details refer to Erb et al., 2009a.

	Cropland in year 2000	Cropland in year 2050	
	[1000 km²]	[1000 km²]	[change]
Northern Africa and Western Asia	763	819	+7.2%
Sub-Saharan Africa	1 781	2 283	+28.2%
Central Asia and Russian Federation	1 572	1 635	+4.0%
Eastern Asia	1 604	1 694	+5.7%
Southern Asia	2 305	2 428	+5.3%
South-Eastern Asia	931	930	-0.1%
Northern America	2 240	2 335	+4.3%
Latin America & the Caribbean	1 685	2 037	+20.9%
Western Europe	862	880	+2.1%
Eastern & South-Eastern Europe	941	890	-5.4%
Oceania and Australia	540	696	+28.8%
World	15 225	16 627	+9.2%

5.2.1. Modulations of human diets

Human diets were considered via caloric per capita food supply according to eleven categories (see Table 8). The medium variant population forecast of the United Nations (2011) was used as a basis of the total food demand calculations in all scenarios. The four diet assumptions were:

1. **Baseline diet**. The baseline assumption for the year 2050 was taken from Erb et al. (Erb et al., 2009a). This scenario assumes that the average value for each region develops towards the national average diet of the country with the highest level in the year 2000 (see Table 9).

2. **Western Diet**. This modulation assumes that all regions develop more quickly towards affluent Western dietary patterns (for details see Erb et al., 2009a, for values refer to Table 9).

3. **Constant diet**. This modulation assumes constant per capita food supply for each regions as values for the year 2000, as reported by FAO's Food Balance Sheets (FAO, 2011b; for values refer to Table 9).

4. **Less meat diet**. This modulation takes the nutritional energy level of the baseline diet as a starting point, and assumes a reduced fraction of animal products per diet. Across all

world regions, the share of protein originating from animal sources was set to 30%. Reduced protein supply was compensated with pulses. This assumption implies a decrease in total protein consumption for the largest animal product consumers (North America, Western Europe), in order to maintain a balance between the remaining food categories.

Table 8.: Assumed levels of per capita food supply in 2050 according to 11 world regions and 11 food categories for the baseline assumption; for details refer to Erb et al., 2009a; values are in kcal per capita and day.

Baseline diet	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania	World
Cereals	1.690	1.400	1.320	1.610	1.500	1.600	996	1.100	990	1.250	1.000	1.426
Roots	60	420	200	130	50	110	106	120	130	190	110	165
Sugarcrops	330	185	410	140	310	300	650	530	420	410	415	300
Pulses	70	90	10	16	95	30	40	110	32	25	20	66
Oilcrops	410	335	290	380	310	380	677	370	520	340	495	372
Vegetables and fruits	220	140	115	190	110	110	216	170	270	152	200	155
Other crops	34	16	21	10	30	10	44	10	50	15	30	22
Meat (ruminants)	100	80	180	75	70	60	127	150	125	100	250	90
Pigs, poultry, eggs	71	40	200	490	50	180	451	290	490	400	310	201
Milk, butter, dairy	200	90	300	50	220	50	420	200	450	350	360	173
Fish	9	5	29	52	6	32	22	13	47	21	24	20
Total	**3.194**	**2.801**	**3.075**	**3.143**	**2.751**	**2.862**	**3.749**	**3.063**	**3.524**	**3.253**	**3.214**	**2.991**
Western diet	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania	World
Cereals	1.338	1.054	1.268	1.309	1.395	1.417	1.140	1.204	1.122	1.123	1.155	1.258
Roots	56	393	177	131	46	90	124	132	155	170	138	159
Sugarcrops	307	176	404	143	277	223	413	423	361	470	384	260
Pulses	58	83	7	12	89	23	50	115	37	21	21	62
Oilcrops	386	394	289	468	293	347	433	270	485	376	462	369
Vegetables and fruits	353	302	354	387	267	303	403	378	394	415	418	329
Other crops	59	43	59	25	78	42	83	34	92	71	68	55
Meat (ruminants)	171	192	157	71	58	59	118	168	104	88	250	114
Pigs, poultry, eggs	184	145	190	655	55	396	423	317	419	444	314	275
Milk, butter, dairy	378	213	367	47	436	68	391	244	384	401	366	269
Fish	9	5	29	52	6	32	22	13	47	21	24	20
Total	**3.300**	**3.000**	**3.300**	**3.300**	**3.000**	**3.000**	**3.600**	**3.300**	**3.600**	**3.600**	**3.600**	**3.170**
Constant diet	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania	World
Cereals	1.671	1.115	1.302	1.605	1.466	1.691	999	1.091	989	1.281	975	1.362
Roots	70	415	182	161	48	107	109	120	137	194	116	169
Sugarcrops	272	112	329	92	237	206	644	479	374	353	381	237
Pulses	72	88	7	15	94	28	44	105	32	24	18	65
Oilcrops	342	249	236	301	251	319	674	306	503	282	459	308
Vegetables and fruits	205	112	109	186	95	107	217	167	274	156	195	144
Other crops	34	16	18	12	28	15	44	15	64	26	32	23
Meat (ruminants)	66	47	126	47	21	19	126	125	115	69	219	56
Pigs, poultry, eggs	71	35	153	433	20	131	452	235	467	350	276	172
Milk, butter, dairy	145	52	294	31	158	22	418	181	428	316	322	137
Fish	9	5	29	52	6	32	22	13	47	21	24	20
Total	**2.958**	**2.247**	**2.784**	**2.935**	**2.425**	**2.677**	**3.748**	**2.836**	**3.431**	**3.072**	**3.017**	**2.692**
Less meat diet	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania	World
Cereals	1.453	1.186	1.633	1.773	1.475	1.738	1.481	1.463	1.480	1.731	1.606	1.491
Roots	62	450	228	176	49	106	189	247	205	262	192	198
Sugarcrops	462	201	398	204	307	275	607	377	365	285	274	300
Pulses	64	77	9	16	95	16	76	140	62	32	46	68
Oilcrops	580	449	285	350	325	300	635	241	492	228	330	384
Vegetables and fruits	183	122	137	203	95	106	322	224	410	210	322	165
Other crops	31	17	23	13	28	15	66	20	96	36	52	27
Meat (ruminants)	82	103	73	33	40	31	44	78	42	42	99	59
Pigs, poultry, eggs	88	78	89	300	37	208	159	147	170	214	124	131
Milk, butter, dairy	180	114	171	21	295	36	147	113	155	193	145	150
Fish	9	5	29	52	6	32	22	13	47	21	24	20
Total	**3.194**	**2.801**	**3.075**	**3.143**	**2.751**	**2.862**	**3.749**	**3.063**	**3.524**	**3.253**	**3.214**	**2.991**

5.2.1.1. Modulations of the composition of animal products with human diets

To assess to what extent different animal products impact resource requirements we have also modulated the composition of animal products within the different diets. For the business-as usual assumption, (BAU) we used the values from the respective human diet scenario.[13] We then added one modulation where we increased monogastric products to 150% of the baseline values (with a maximum level of 75% in total animal products; "Monogastric") and another modulation where we reduced this value to 50% of the baseline ("Ruminant"). We altered the amount of ruminant meat and milk proportionally to always end up with the same overall amount of calories from animal products.

5.2.1.2. Modulations of agricultural yields

Agricultural yields for 2050 were modulated for the eleven world regions and seven crop categories. For the baseline scenario ("conventional yields"; Conv), the yields derived from FAO projections (Bruinsma, 2003; Alexandratos et al., 2006) were used (for details see Erb et al., 2009a).

These reports are the most authoritative sources for forecasts on development of crop production, yields and area expansions available today, containing growth rate projections for crop production for selected important food crop groups (cereals, oil crops, and sugar), with regional resolution. From information on the sources of growth in crop production, which is, on the relative contribution of area expansion, yield increases and changes in cropping intensity[14] to the increases of overall production, and data on production, area harvested and agricultural yields in 2000 (Krausmann et al., 2008), the yields for 7 crop groups (cereals, oil-bearing crops, sugar crops, pulses, roots and tubers, vegetables and fruits, and other crops) were derived. As the FAO does not report projections for fodder crop production up to 2050, we assumed that the share of fodder crops to the overall arable land remains constant and that the yields of fodder crops develop over time with the same rate of change as the aggregate 'other crops'.

The scenario elaborated by the FAO describes a world in which agricultural intensification progresses rapidly: yields are forecasted to reach very high levels for some crops and regions. Overall production on cropland is assumed to increase by 68% (dry matter), with a maximum increase of +154% and +121% for Sub-Saharan Africa and Latin America, respectively. This is mainly due to increases in land-use yields (i.e. the combined effect of harvest yields and changes in cropping intensity), which increases by 54% on average of the total cropland, and to a much lesser extent by area expansion.

[13] It should be noted at this point that the calculation of the baseline diet scenario resulted in a reduced global per-capita monogastric product consumption as compared to the 2050 level. This is not in line with the assumptions on the development of meat production found in the literature. With the modulations of the composition of animal products in the diet, however, we are able to show the effects of such disparities.

[14] Cropping intensity is defined as the annually harvested area expressed as a percentage of the total cropland area including fallows. In FAO statistics, harvest areas are counted each time when they are harvested, whereas land use areas refer to the extent of land used as cropland or cropland left fallow. Harvest area can exceed cropland area including fallow in the case of multicropping. In areas with no multicropping, harvest area is equal to cropland area excluding fallow.

It has to remain unclear today if the impressive yield gains in the Conv-scenario can be realized. Some biologists argue that a continuation of past yield increases, as assumed by the FAO, seems unlikely because most of the best quality farmland is already used and rates of yield increases are already declining (e.g., rice in South-Eastern Asia) or yields have even become stagnant (e.g., rice in Japan, Korea, China) as they approach limits set by soil and climate. Also, many options to achieve yield gains have already been discovered and are approaching physiological limit, such as further improvements of harvest indices (increasing the fraction of desired product, e.g. grain, at the expense of supporting tissues such as leaves and stems;). Soil degradation and depletion of nutrient stocks in soils is seen as an additional challenge (Tilman et al., 2002). On the other hand, improvement of management practices could help to maintain growth in yields, mostly due to improved stress tolerance, avoidance of nutrient and water shortages, improvements in pest control, etc. In any case, substantial investments will be indispensable for maintaining growth in crop yields (for details and references see Erb et al., 2009a).

In order to explore the option space of future developments, two modulations of the baseline development of agricultural yields were developed:

1. Low yields: For the modulation with low agricultural yields we took values from the earlier studies (Erb et al., 2009a) that assume yield levels at 60% of the baseline yields for intensive production systems (not for systems currently in subsistence agriculture). These lower yields are in line with assumptions of yields obtained with organic farming and reflect the fact that organic farming practices require additional area for crop rotations to maintain soil fertility. These yield reductions were applied only to intensive production systems, and not to extensive or traditional production system. In consequence, for regions with a low share of industrial agriculture (e.g. Sub-Saharan Africa), the reductions compared to the CON yield scenario are moderate (see Figure 23; for detail see Erb et al., 2009a).

2. High yields: For the high yield level modulation we assumed all yields to be at 109% of the baseline, reflecting an optimistic yield development assumption, based on high levels of external inputs. This assumption draws from an analysis of agricultural scenarios in the Millennium Ecosystem Assessment (MEA; Millennium Ecosystem Assessment, 2005b) which revealed that the 'TechnoGarden' scenario contained therein was comparable with FAO forecasts, and that the highest yield scenarios in MEA ('Global Orchestaration') reach a 9% higher yield level.

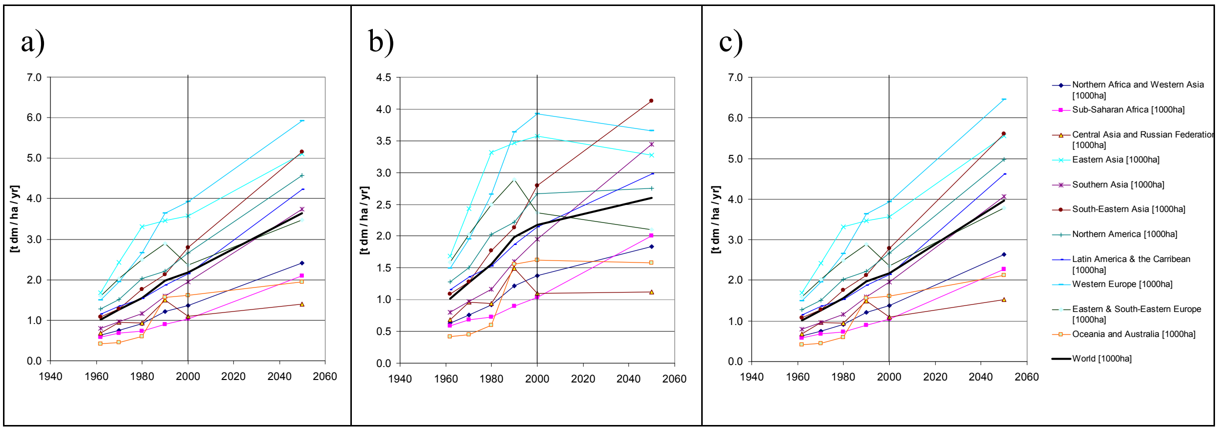

Figure 23: Agricultural yields development 1960 - 2050 in regional break-down. a) the baseline scenario ("conventional yields"; Conv) scenario, b) the low yield scenario (Low), and c) the high yield scenario (High). These data are available separately for 11 world regions and 7 crop categories; for details refer to Erb et al., 2009a; values in tons dry matter per hectare and year.

5.2.1.3. Modulations of livestock diets and efficiencies

For livestock diets, we assumed four modulations, each containing values of feed demand for ruminant meat, monogastric products and milk expressed in kg dry matter crop feed and kg dry matter roughage feed per kg dry matter output of the respective product category. The trend-scenario ("TREND") is based on Bouwman et al. (2005): this study provides projections of developments in livestock production for 2030 with special focus on the ruminant sector. Their values on feed intake and product output for different world regions and livestock systems are based on data in Seré et al. (1996). From the data for 2030 we extrapolated values for 2050 assuming the same linear development as assumed from 1995 to 2030 in the study. For our data we aggregated beef and mutton and goat meat into the ruminant meat category and pig meat, poultry meat and eggs into the monogastric category on the product side, and the grass, residues and fodder, and scavenging into the roughage feed category on the feed demand side. As the study distinguished more world regions than we do in this report we aggregated them into the eleven we use here. Table 8 presents the used values for the baseline scenario.

Three modulations of the baseline livestock input-output efficiency were assumed:

1. Intensive path: The first modulation of the baseline livestock diet is based on the assumption of further grain based intensification within this sector: more crop products will be fed to the animals, reducing their demand for roughage. For this we assumed crop feed demand at 130% of the baseline level around the globe and accordingly lowered roughage demand (by twice the amount of increased crop feed intake, i.e. assuming a substitution weight of 0.5). To avoid extreme results, we set the following absolute boundaries, based on values for regions that already employ intensive livestock rearing: at least 5 and 1 kg dm feed crops per kg dm ruminant meat and milk, respectively; at most 8 kg dm crop feed per kg dm monogastric products. And a maximum of 30 and 10 kg dm roughage feed per kg dm ruminant meat and milk, respectively, and at least 0.5 kg dm

roughage feed per kg dm monogastric product (for detailed values refer to Table 5). These scenario assumptions represent a massive proliferation of intensive, industrialized livestock systems at the global scale.

2. Intensive path with roaming: Grain based livestock systems can also employ higher standards of animal welfare. Accordingly, in a second modulation of the baseline, we assumed factors at 105% of those in the second modulation to account for higher feed demand for roaming animals, and added an allowance for converting a certain amount of cropland into range area. The values for free range area demand of pigs and poultry were taken from Erb et al. (2009a) and are 0.42 ha/tdm/yr, referring to meat production.

3. Extensive path: For the third modulation in livestock diets, we assumed an extensification of the livestock sector, leading to more roughage based diets: feed crop demand in all livestock diets were halved from the baseline assumption, and roughage demand was increased accordingly (by twice the amount of the reduction in cropland feed). As monogastrics require a certain level of input of crop products in their diets, we assumed the same values as in the baseline scenario for them. This scenario results in an increased area demand for roughage production and thus allows for space for free ranging of all livestock (for detailed values refer to Table 5).

Table 9. Livestock conversion efficiencies (ratio input/output dry matter) of market feed (feed crops) for 2050 according to the TREND scenario, intensive path, intensive plus roaming path and extensive path. For the TRED assumption, as well as the intensive and extensive path assumptions; values are based on Bouwman et al., 2005. For the fourth scenario 'Intensive with roaming' (not shown), an additional area requirement for roaming was added, but the input-output efficiency is the same as with the 'intensive path' scenario. For details see text.

TREND	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania
feed crops											
Meat (ruminants)	5,4	0,9	5,9	9,1	1,3	6,4	12,9	3,6	2,2	8,5	0,8
Pigs, poultry, eggs	7,1	5,0	7,7	4,0	4,4	3,9	6,4	5,8	6,8	7,8	6,2
Milk, butter, dairy	2,3	0,9	2,0	3,1	0,5	0,9	3,0	1,8	1,4	2,8	0,3
roughage											
Meat (ruminants)	29,5	70,9	35,7	52,4	68,7	89,0	38,0	94,3	18,6	42,8	59,9
Pigs, poultry, eggs	1,8	5,5	3,0	6,5	4,6	6,5	3,1	4,1	3,9	3,2	3,8
Milk, butter, dairy	7,3	22,2	7,0	9,8	16,8	8,1	4,3	18,1	8,0	5,9	8,5
intensive path	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania
feed crops											
Meat (ruminants)	7,0	5,0	7,7	11,8	5,0	8,4	16,7	5,0	5,0	11,1	5,0
Pigs, poultry, eggs	8,0	6,5	8,0	5,2	5,8	5,1	8,0	7,5	8,0	8,0	8,0
Milk, butter, dairy	3,0	1,2	2,6	4,0	1,0	1,1	3,9	2,3	1,8	3,6	1,0
roughage											
Meat (ruminants)	26,3	30,0	30,0	30,0	30,0	30,0	30,0	30,0	13,0	30,0	30,0
Pigs, poultry, eggs	0,5	2,5	2,3	4,1	1,9	4,1	0,5	0,6	1,5	2,8	0,5
Milk, butter, dairy	5,9	10,0	5,8	7,9	10,0	7,5	2,5	10,0	7,1	4,3	7,1
extensive path	NAWA	SSAfrica	CARussia	EAsia	SAsia	SEAsia	NAmerica	LAmerica	WEurope	EEurope	Oceania
feed crops											
Meat (ruminants)	2,7	0,4	3,0	4,5	0,7	3,2	6,4	1,8	1,1	4,3	0,4
Pigs, poultry, eggs	7,1	5,0	7,7	4,0	4,4	3,9	6,4	5,8	6,8	7,8	6,2
Milk, butter, dairy	1,2	0,5	1,0	1,5	0,3	0,4	1,5	0,9	0,7	1,4	0,2
roughage											
Meat (ruminants)	34,9	71,8	41,6	61,5	70,0	95,4	50,9	97,9	20,8	51,4	60,7
Pigs, poultry, eggs	1,8	5,5	3,0	6,5	4,6	6,5	3,1	4,1	3,9	3,2	3,8
Milk, butter, dairy	9,6	23,1	9,0	12,8	17,3	8,9	7,3	19,8	9,3	8,7	8,8

5.2.2. Results and discussion

Applying full factorial design to these different modulations yield a total of 144 combinations. The results of these 144 scenarios were used to empirically analyse the interrelations between changes in the livestock systems, dietary changes and agricultural technology changes. Results of the scenario analysis are displayed in Figure 24.

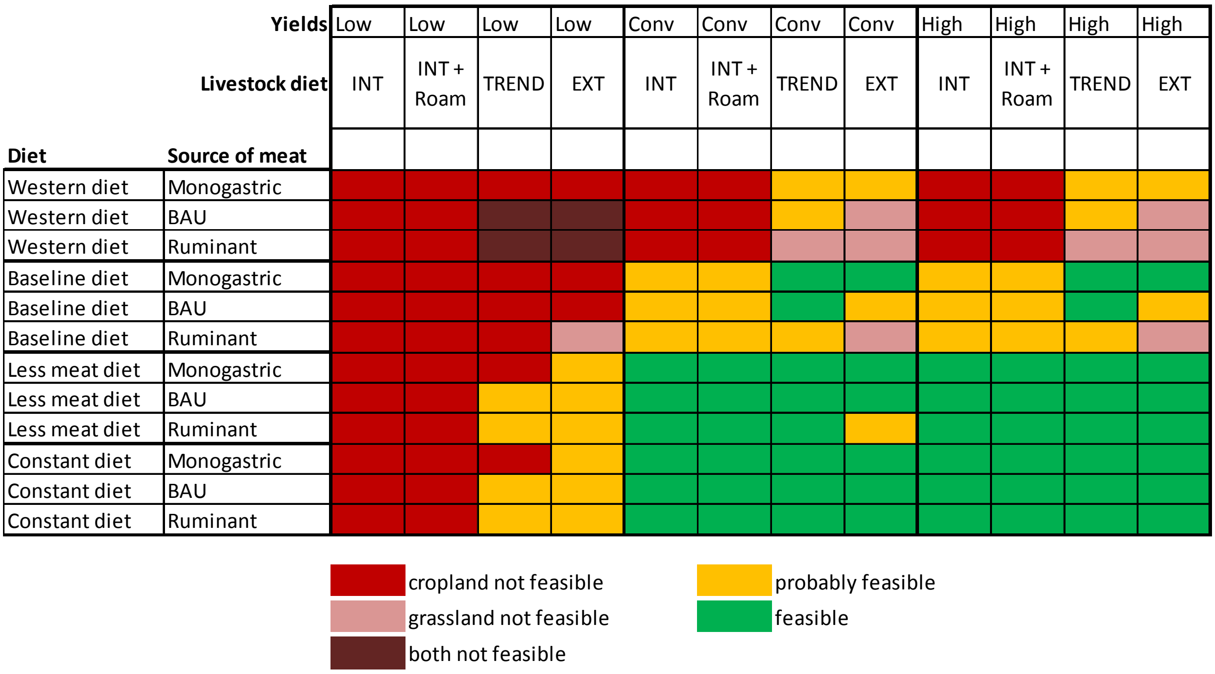

Figure 24. Feasibility analysis of all 144 scenarios in 2050. Marked: combination of all business as usual scenarios in 2050.

For visualization purposes we grouped human diets and the modulation of the composition of animal products within the diets on the vertical axis, and the levels of agricultural yields together with livestock diets on the horizontal axis. We arranged the results from scenarios with higher levels of cropland product demand on the top right corner to scenarios with lower levels of cropland product demand on the lower right corner (see Figure 24). We considered a scenario feasible, if global cropland product demand was above 105% of the global production in the respective scenario, and global grazing intensity was below 27% (150% of the 2000 value; or an increase of global grazing intensity by 50%) of total global; scenarios where these values were below 95% or above 42% (a theoretical maximum of grazing intensity, taking grazing land qualities into account; see Erb et al., 2007), respectively were considered not feasible. Scenarios in between these thresholds were considered probably feasible.

53 out of 144 scenarios are found to be feasible within the given supply scenario of yields and area expansion. The same number of scenarios is found to be not-feasible because cropland production is not sufficient to cover demand for cropland products. 9 scenarios are found to be infeasible due to an exceeding grazing intensity above maximum level of 42%. Four scenarios are found to be impossible due to a prohibitive grazing intensity and insufficient cropland production. 33 scenarios are found to be probably feasible.

It is important to note at this point that scenarios may be unfeasible (or undesirable) for other reasons than insufficient cropland area or excessive grazing intensity. For example, due to economic (e.g. lacking investments) or biophysical reasons (e.g. soil degradation, climate change, lacking resources such as water or nitrogen) it might be impossible to actually achieve the yield levels as projected by the FAO for the year 2050, or the livestock efficiencies as assumed here. Furthermore, feedbacks such as possible future reductions in yield levels resulting from poor management or inappropriate agricultural technologies (e.g., soil degradation, pest outbreaks due to unsustainable cropping practices, salinization resulting from poor irrigation techniques, etc.) would have to be considered. Determining the infeasibility of scenarios for such reasons is, however, outside the scope of this study.

The feasibility analysis reveals that high dietary levels would only be hardly achievable within the limits set in this study, in particular within the assumed 9% increase in cropland area. A monogastric based animal share in the human diet apparently is favourable to reach feasibility within the set limits, as well as the prevalence of extensive (more roughage based) livestock systems. The business-as-usual diet would become feasible at conventional yield levels, but dominance of ruminant products would not be possible. More extensive (i.e. more roughage based) livestock system would be advantageous over grain-based livestock diets. However, a ruminant-based diet would not be feasible with extensive livestock systems due to resulting excessive grazing intensity.

A fair, vegetarian diet would require less intensive agriculture to become feasible, here again extensive livestock systems have a positive, i.e. resource sparing effect. Grazing land is not limiting at this dietary level.

At the same time, the option space for low yield levels in agriculture, such as those that would be achieved with organic farming practices, is narrow, found to be probably feasible only with vegetarian diets or with a food supply held constant at per-capita dietary levels of the year 2000, concomitant with extensive livestock systems.

Extensive (roughage based) livestock system are found to be favourable for more frugal diets. Rich diets, in contrast, lead to prohibitive grazing intensities with extensive livestock systems.

Grain based livestock systems, characterized by increased overall input-output efficiencies, but decreased crop feedstuff efficiencies, can only support business as usual or more frugal diets, but not rich, western-type diets, due to the limits of cropland expansion set in this modelling exercise. Here, indeed cropland is the limiting factor, whereas grazing intensities are still at low levels, despite the huge differences in the amount of animal products consumed in the rich diets (see also Figure 25).

Interestingly, the variant to additionally take area for roaming into account does not alter significantly this feasibility space of grain-based livestock diets. This can be interpreted as an indication that area provision for reasons of animal welfare is possible without leading directly to land use conflicts or competing land uses.

Cropland: supply / demand

Diet	Source of meat	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Western diet	Monogastric	66%	69%	74%	80%	84%	86%	97%	105%	91%	92%	107%	114%
Western diet	BAU	66%	69%	76%	83%	85%	86%	100%	110%	92%	92%	109%	118%
Western diet	Ruminant	66%	69%	76%	88%	84%	86%	100%	115%	91%	92%	108%	124%
Baseline diet	Monogastric	76%	78%	85%	89%	97%	97%	109%	115%	104%	104%	118%	124%
Baseline diet	BAU	76%	78%	86%	93%	97%	97%	111%	120%	105%	104%	120%	129%
Baseline diet	Ruminant	76%	78%	87%	97%	96%	96%	112%	126%	104%	104%	120%	136%
Less meat diet	Monogastric	85%	87%	95%	99%	110%	111%	124%	128%	119%	119%	133%	138%
Less meat diet	BAU	85%	87%	96%	101%	111%	112%	125%	131%	119%	120%	134%	141%
Less meat diet	Ruminant	85%	87%	97%	104%	110%	111%	125%	135%	119%	119%	134%	145%
Constant diet	Monogastric	85%	86%	94%	99%	108%	107%	121%	127%	117%	115%	130%	137%
Constant diet	BAU	86%	87%	95%	102%	109%	108%	122%	131%	117%	116%	132%	142%
Constant diet	Ruminant	86%	87%	96%	106%	107%	106%	122%	137%	116%	114%	133%	150%

Grazing land: grazing intensity

Diet	Source of meat	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Western diet	Monogastric	12%	13%	36%	39%	10%	11%	34%	37%	9%	10%	33%	36%
Western diet	BAU	16%	17%	43%	47%	14%	15%	42%	45%	13%	14%	41%	44%
Western diet	Ruminant	25%	27%	62%	68%	23%	25%	60%	66%	22%	24%	59%	65%
Baseline diet	Monogastric	4%	5%	21%	23%	2%	3%	19%	21%	1%	2%	18%	20%
Baseline diet	BAU	8%	9%	28%	31%	6%	7%	26%	29%	5%	6%	25%	28%
Baseline diet	Ruminant	15%	16%	41%	46%	13%	14%	39%	44%	12%	13%	38%	43%
Less meat diet	Monogastric	0%	1%	13%	14%	0%	0%	11%	12%	0%	0%	10%	11%
Less meat diet	BAU	2%	3%	17%	19%	0%	1%	15%	17%	0%	0%	14%	16%
Less meat diet	Ruminant	7%	8%	26%	29%	5%	6%	24%	27%	4%	5%	23%	26%
Constant diet	Monogastric	0%	0%	9%	11%	0%	0%	8%	9%	0%	0%	7%	8%
Constant diet	BAU	1%	2%	14%	17%	0%	0%	12%	15%	0%	0%	11%	14%
Constant diet	Ruminant	7%	8%	24%	29%	5%	6%	23%	27%	4%	5%	22%	26%

Feasible — Probably feasible — Not feasible

Figure 25. Feasibility analysis of all 144 scenarios in 2050, break-down to a) cropland, and b) grazing land. a) displays the global cropland demand-supply ratio, b) the obtained grazing intensities. Numbers indicate for cropland (a) the global ratio of area supply to area demand, for grazing (b) the grazing intensity expressed as harvested (grazed) biomass per annual aboveground net primary production of grazing lands.

Figures 25 a) and b) give the global demand-supply ratios for cropland area as well as the grazing intensity values obtained in each scenario. This break-down allows scrutinizing in detail the quantitative interrelations between the livestock sector and food availability.

In general, more resource intensive diets require more cropland area (decreasing the global "demand-supply ratio") and result in increased grazing intensities. In contrast, increases in the intensity of livestock systems (roughage-based to grain-based livestock diets) result in decreased cropland feasibility, but lessen the pressure on grazing land. In general, Figure 25 reveals that, within the set cropland expansion scenario, grazing land is much less limiting than cropland. However, a stronger cropland expansion would alleviate the pressure on cropland, at the expense of increased grazing intensity, because animal production on grazing land would have to be sustained on smaller areas.

Such a trade-off between cropland demand and grazing intensity can be found in all scenarios: For example, a dominance of monogastric species requires comparatively more cropland, but less roughage (and thus less grazing intensity) than a ruminant dominated diet. This is particularly the case with more vegetarian diets; here, grazing intensity is particularly low. The more meat-based constant 2000 diet, instead, shows relatively larger grazing intensities, at more or less equal cropland demand-supply ratios.

The business as usual scenario combination results in a cropland demand-supply ratio of 109%, i.e. 9% of the assumed cropland are not required for food production (1.1 million km²). This area could be utilized for other purposes, e.g. bioenergy production (yielding approximately 18 EJ/yr primary energy from dedicated cropland, assuming potential productivity, i.e. the hypothetical NPP under no-land use assumptions, on this area), but also for alleviating the environmental pressures (less intensive agriculture, less land under cropland use) or allowing for richer diets. It is beyond the scope of this study to assess these alternatives, as we here aim at understanding the role of livestock systems in the biomass production-consumption system.

This "free" potential is particularly large in the combination of high yields and constant 2000 per-capita diets. This, however, is an extremely improbable scenario combination, as it would entail a shift in the paradigm of agricultural production, away from a food producing mandate, strongly related to food security.

The option space reveals that the here assumed variation in the source of animal products in human diets (monogastric dominated vs. ruminant dominated) is not resulting in large discrepancies with regard to the cropland-feasibility of a scenario, but in quite substantial differences in grazing intensity. In contrast, the different assumptions on the diet of livestock systems (grain based intensive vs. roughage based extensive) is found to exert a much stronger effect, both on cropland and grazing land.

The cropland yield level is exerting only a limited effect on grazing intensity, whereas it is the major determinant of cropland feasibility next to the human diet. Human diets exert a very strong effect on grazing intensity, but the livestock diet (or system) seems to be a determining factor of a similar if not even stronger weight. With regard to human diet, the share of meat seems to be decisive. The vegetarian diet, that substitutes milk and eggs for meat, shows the lowest grazing intensities across all scenarios. This can be explained by the fact that milk, according to the results by Bouwman et al. (2005), is much more input-output efficient than ruminant meat production.

Regional results

The global biomass balance model allows analysing effects of the different scenario assumptions not only at the global level, but also at the regional level. At the regional level, however, the results must not be interpreted at the level of “feasible” vs. “non-feasible”, as the biomass balance is calculate at the global level. Instead, those scenarios that are feasible at the global scale differ in the regional self-sufficiency rate for cropland products, or in their grazing intensity. The gap between regional production and demand, for meat as well as for cropland products, is assumed to be balanced by trade: for example, regions where the demand for primary products (e.g. cereals) exceeds regional supply are net importing regions; regions where biomass supply is larger than regional demand are net exporters.

Nevertheless, regions with low purchasing power or failing institutions may not be in the position to import the required food or to distribute these imports fairly. Thus, it may be legitimate to interpret decreased self-sufficiency as increased vulnerability towards food insecurity in such regions (Naylor and Falcon, 2010). We here present results for two regions that allow gaining insights on the interplay of trajectories in the livestock sector, diets and cropland yields and self-sufficiency rations for cropland products on the regional level. The first case is Sub-Saharan Africa, the region for which many authors assume large “land reserves” to exist, that could be used for bioenergy production. The second case is East Asia, the region currently characterized by massive changes in almost all aspects of the biomass production and consumption system, concomitant with considerable population increases. Regional results for the other regions can be found in the Annex.

Figure 26 displays the regional result for Sub-Saharan Africa. The business as usual scenario results in a rather low self-sufficiency rate of 66% (i.e. two third of the consumed cropland products stem from domestic production, one third is imported) and a grazing intensity of 13%. Apparently, this region experiences a shortage of cropland production and at the same time it is characterized by abundant land currently used for grazing purposes. In our scenario framework, assuming only moderate increases of cropland yields for this region (in line with the FAO prospect; Bruinsma, 2003; Alexandratos et al., 2006; Erb et al., 2009a), cannot keep pace with population growth. Only in the constant human diet scenario, which assumes the currently prevailing very low nutritional levels of this region not to change, the trade deficit is somewhat alleviated.

For Sub-Saharan Africa, organic yields and rich diets are found to have decreasing effects on the regional self-sufficiency ratio. Also, intensive livestock diet systems seem to aggravate the import deficit of cropland products in this region. These intensive systems are at the same time associated with reductions in grazing intensity; however, grazing intensity is comparatively low in all scenarios, except those scenarios of the Western diet that are feasible at the global scale.

a)

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
SSAfrica													
Western diet	Monogastric	-	-	-	-	-	-	0,51	0,54	-	-	0,56	0,59
Western diet	BAU	-	-	-	-	-	-	0,52	-	-	-	0,56	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,63	0,65	0,66	0,68	0,68	0,71	0,71	0,73
Baseline diet	BAU	-	-	-	-	0,63	0,66	0,66	0,68	0,68	0,71	0,72	0,73
Baseline diet	Ruminant	-	-	-	-	0,63	0,66	0,66	-	0,68	0,71	0,72	0,74
Less meat diet	Monogastric	-	-	-	0,63	0,59	0,62	0,63	0,66	0,64	0,68	0,69	0,71
Less meat diet	BAU	-	-	0,61	0,63	0,60	0,63	0,64	0,66	0,65	0,68	0,69	0,71
Less meat diet	Ruminant	-	-	0,62	0,64	0,60	0,63	0,64	0,66	0,65	0,68	0,69	0,71
Constant diet	Monogastric	-	-	-	0,81	0,79	0,82	0,82	0,84	0,86	0,88	0,91	0,93
Constant diet	BAU	-	-	0,80	0,81	0,79	0,82	0,82	0,84	0,87	0,88	0,93	0,95
Constant diet	Ruminant	-	-	0,80	0,81	0,80	0,82	0,83	0,84	0,88	0,89	0,97	1,00

b)

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
SSAfrica													
Western diet	Monogastric	-	-	-	-	-	-	0,41	0,41	-	-	0,40	0,41
Western diet	BAU	-	-	-	-	-	-	0,49	-	-	-	0,48	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,03	0,03	0,14	0,15	0,02	0,02	0,14	0,14
Baseline diet	BAU	-	-	-	-	0,03	0,04	0,16	0,17	0,03	0,03	0,16	0,16
Baseline diet	Ruminant	-	-	-	-	0,04	0,05	0,19	-	0,04	0,04	0,18	0,19
Less meat diet	Monogastric	-	-	-	0,20	0,05	0,05	0,19	0,19	0,04	0,05	0,18	0,19
Less meat diet	BAU	-	-	0,24	0,24	0,06	0,07	0,23	0,24	0,06	0,07	0,23	0,23
Less meat diet	Ruminant	-	-	0,28	0,29	0,08	0,09	0,28	0,28	0,08	0,09	0,27	0,28
Constant diet	Monogastric	-	-	-	0,06	-	-	0,05	0,05	-	-	0,05	0,05
Constant diet	BAU	-	-	0,07	0,08	-	-	0,07	0,07	-	-	0,07	0,07
Constant diet	Ruminant	-	-	0,09	0,10	0,00	0,01	0,09	0,09	-	0,00	0,09	0,09

Decreased self sufficiency
Self sufficiency close to BAU
Increased self sufficiency

Decreased grazing intensity
Grazing intensity similar to BAU
Increased grazing intensity

Figure 26. Scenario results for Sub-Saharan Africa in 2050. a) Cropland demand-supply ration (= self-sufficiency for cropland products), b) grazing intensity. Colouring indicates similarity or distance (± 10%) to the combination of all baseline and trend scenarios (red mark).

Figure 27 displays the regional results for the region of East-Asia, a region dominated by China, and characterized by a very high population density. This region, in the combination of all baseline scenarios, is a net exporter, supply of cropland products being 10% larger than the regional demand. Grazing intensity, in contrast, is with 44% in the BAU scenario extremely high, and at levels that would require optimal management in order to warrant sustainable grazing regimes. However, the regional grazing intensity result is not to be interpreted as a "real" pressure on the grazing lands within the region. It can also indicate import dependency with regard to ruminant products.

In the case of East Asia, we again find that high cropland yields increase self-sufficiency, as well as extensive grazing systems and more frugal diets. Low yields, in contrast, or intensive, grain-based livestock systems, may result in a reversal of the direction of the net-trade flow, and the region could become import-dependent to a certain degree.

a)

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	**Source of meat**												
EAsia													
Western diet	Monogastric	-	-	-	-	-	-	1,02	1,09	-	-	1,10	1,17
Western diet	BAU	-	-	-	-	-	-	1,03	-	-	-	1,11	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,99	0,98	1,10	1,16	1,07	1,05	1,18	1,24
Baseline diet	BAU	-	-	-	-	0,99	0,97	1,09	1,16	1,07	1,04	1,18	1,25
Baseline diet	Ruminant	-	-	-	-	0,91	0,91	1,00	-	0,97	0,96	1,08	1,26
Less meat diet	Monogastric	-	-	-	0,85	1,14	1,12	1,21	1,24	1,23	1,21	1,31	1,34
Less meat diet	BAU	-	-	0,83	0,85	1,14	1,12	1,21	1,24	1,22	1,21	1,30	1,34
Less meat diet	Ruminant	-	-	0,80	0,84	1,06	1,04	1,14	1,26	1,14	1,12	1,23	1,35
Constant diet	Monogastric	-	-	-	0,85	1,09	1,06	1,19	1,24	1,17	1,15	1,28	1,33
Constant diet	BAU	-	-	0,82	0,85	1,09	1,07	1,19	1,24	1,18	1,15	1,29	1,33
Constant diet	Ruminant	-	-	0,77	0,84	0,99	0,98	1,10	1,26	1,06	1,04	1,18	1,35

b)

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	**Source of meat**												
EAsia													
Western diet	Monogastric	-	-	-	-	-	-	0,64	0,74	-	-	0,63	0,73
Western diet	BAU	-	-	-	-	-	-	0,54	-	-	-	0,53	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,22	0,24	0,46	0,53	0,21	0,23	0,44	0,52
Baseline diet	BAU	-	-	-	-	0,24	0,26	0,49	0,57	0,23	0,25	0,48	0,55
Baseline diet	Ruminant	-	-	-	-	0,66	0,70	1,20	-	0,65	0,69	1,18	1,41
Less meat diet	Monogastric	-	-	-	0,23	0,04	0,05	0,15	0,18	0,02	0,03	0,14	0,17
Less meat diet	BAU	-	-	0,22	0,25	0,04	0,05	0,17	0,20	0,03	0,04	0,15	0,19
Less meat diet	Ruminant	-	-	0,65	0,78	0,30	0,33	0,60	0,73	0,29	0,31	0,59	0,72
Constant diet	Monogastric	-	-	-	0,44	0,15	0,16	0,34	0,39	0,14	0,15	0,32	0,38
Constant diet	BAU	-	-	0,36	0,40	0,13	0,14	0,31	0,36	0,12	0,13	0,29	0,34
Constant diet	Ruminant	-	-	0,98	1,17	0,50	0,53	0,93	1,12	0,49	0,52	0,92	1,11

Decreased self sufficiency
Self sufficiency close to BAU
Increased self sufficiency

Decreased grazing intensity
Grazing intensity similar to BAU
Increased grazing intensity

Figure 27. Scenario results for East Asia in 2050. a) Cropland demand-supply ration (= self-sufficiency for cropland products), b) grazing intensity. Colouring indicates similarity or distance (± 10%) to the combination of all baseline and trend scenarios (red mark).

However, according to our results, the major concern is with grazing land resources in this region. Extensive livestock systems are found to be associated with increased pressures on grazing land, as well as a dominance of ruminant-based animal products in human diets. These combinations even reach grazing intensities above 1, that “in reality” are not possible (Grazing harvest can by definition not exceed grazing productivity, because annual plants dominate). In these cases, East Asia would become import dependent for ruminant products. Only a vegetarian diet is found to have positive effects on these high levels of grazing land intensity.

6. Conclusions

Livestock systems intimately relate to the biomass production system and to food security. First of all, livestock plays a central role in providing nutritional energy to humans. Furthermore, livestock systems fulfil several other functions for society, and therefore also indirectly relate to food provision and thus food security.

In this study, we identify 10 mechanisms or “hot spots” of the interrelation between livestock systems and food security, namely a) competing land uses (yield increases vs. agricultural expansion), b) altered input/output relations (Breeding & GMO), c) changes in the mix of livestock (from ruminants towards a dominance monogastric species), d) animal diseases and health risks, e) loss of the multi-functionality of livestock with market orientation, f) resource use conflicts (food/feed/energy). g) human health issues of overconsumption and malnutrition, h) use of waste flows and residues, including manure management, i) increased production due to economies of scale vs. self-sufficiency, and j) reductions of subsistence livestock systems and impacts on opportunities for non-agricultural employment/income.

Some of these interrelations can be quantified by calculating the options space with a biophysical biomass balance model. By consistently combining scenario assumptions on the development of diets, agricultural technologies, and the livestock system, we can gain insights in the effects of a more grain-based livestock diet on the option space of future developments, at the global and the regional scale. As food security is in the focus of research, we here present regional results for two regions only, Sub-Saharan Africa and East Asia.

According to our findings, a strategy towards more grain based livestock systems (the common path of livestock intensification) will have strong effect on cropland demand-supply ratios, with a high potential to trigger land use competition on cropland. Such a strategy would also reduce the resource base of human society, as a major function of livestock can be seen in converting non-edible resources (e.g. grass, residues) into edible ones. On the other hand, a grain-based intensification strategy, would allow reducing overall area demand of food production, and so allow for keeping grazing intensities low.

However, we find that the quantity and quality of diet is a decisive factor for any future development. More modest diets, with a lower share of animal products, tend to keep the option space open. In contrast, rich, animal-based diets reduce the option space, e.g. towards a more rigorous cropland intensification pathway. Rich diets are found to hit the margins of feasibility due to the limited amount of either cropland or grazing land (limits of grazing intensity), or both.

The effect of grain-based intensification of the livestock sector is thus double-edged: Intensive livestock systems allow for increased production on smaller land areas, and for the provision of cheaper products. This could benefit in particular the urban poor that have limited economic resources and no access to land. On the other hand, grain-based livestock intensification might result in land use conflicts and, through price effects, exclude smallholders from market access. This might in particular affect pastoralists.

Another disadvantage of intensified, in particular land-less livestock systems is the breaking up of nutrient cycles, which results in areas of nutrient depletion and areas of nutrient concentration and subsequent problems of e.g. water contamination. Mixed systems, in contrast, have the advantage to be potentially able to hold nutrients in smaller cycles, as manure (a valuable fertilizer) will be available at the farm and so reduce the demand for mineral fertilizers.

Furthermore, if the land-saving advantage is overcompensated by increased consumption levels, this might result in an increased cropland area demand that will contribute to further pushing other land uses, such as grazing, to untouched ecosystems, and consequently trigger a plethora of detrimental ecological effects.

Our empirical results also indicate that future paths will not inevitably have to be based on full-scale intensification strategies, and more moderate development strategies seem possible, if they are accompanied with strategies that aim at an integrated optimization of production and consumption at the same time. In particular a vegetarian diet is found to have positive effects, strongly positive for grazing land, and slightly positive even for cropland.

We also find that land competition is not an argument against programmes that allow for roaming space, even in intensive livestock production systems. This area requirement is apparently small in contrast to the demand for feedstuff production and does only insignificantly affect the option space of the scenario analysis.

The regional analysis reveals that the regional context is important. Regions are differently endowed with cropland and grazing land resources. Strategies that are positive in one regional context, such as extensification of the livestock systems in Sub-Saharan Africa, where grazing land is not limiting, might not be successful or desirable in other regions. In East-Asia, for example, our biophysical analysis reveals that much stronger limits relate to grazing than to cropland. Here, extensive livestock systems might not be supportable by the existing grazing land. In such cases, again, integrated approaches that aim at reducing meat and milk consumption might be favourable from a biophysical perspective.

It should be noted, however, that our biophysical analysis is based on a limited set of scenarios. Especially, we only assume one cropland expansion scenario, that shows a moderate (+9%) global rate of cropland expansion until 2050. Larger cropland area increases cannot be ruled out in the future, and our result for the Western-type of human diets points in the direction that this might become even probable if such a consumption path proves to be desired. Cropland expansion, however, will increase pressures on other land ecosystems, either increasing grazing intensity on the remainder areas, or push land use further into pristine ecosystems (e.g. forests). Similar effects would have large scale strategies that aim at fostering the production of bioenergy from dedicated crops.

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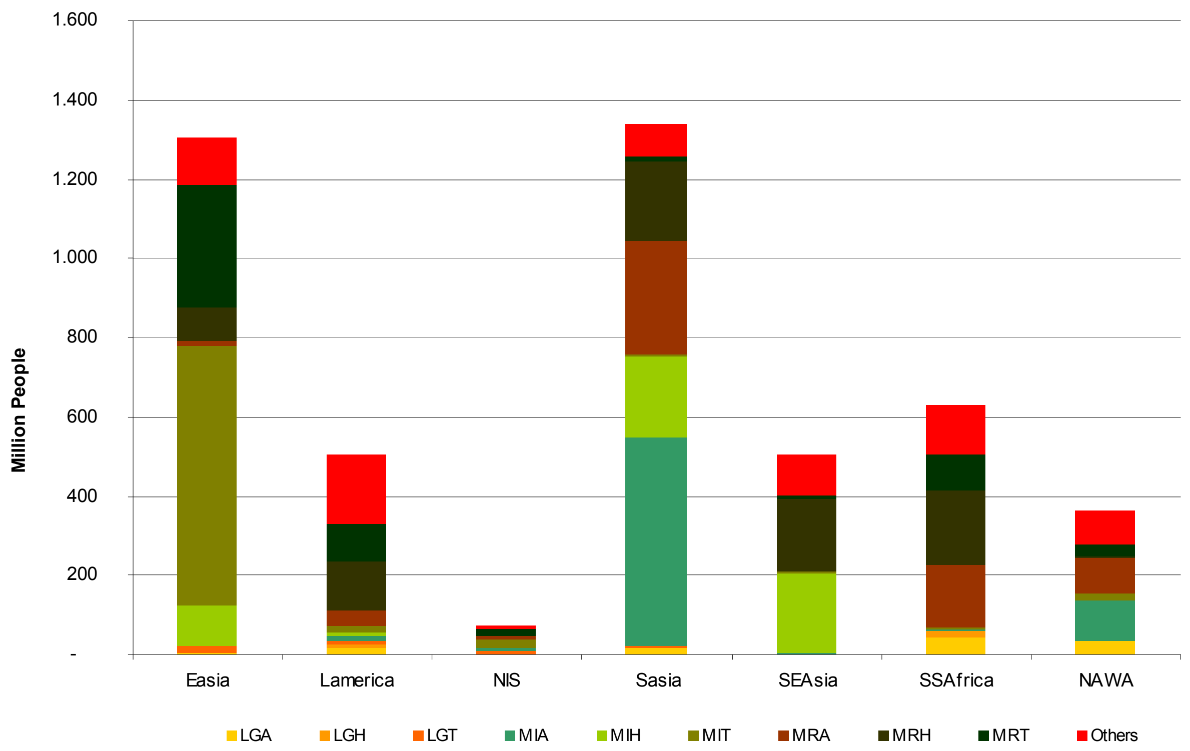
8. Annex

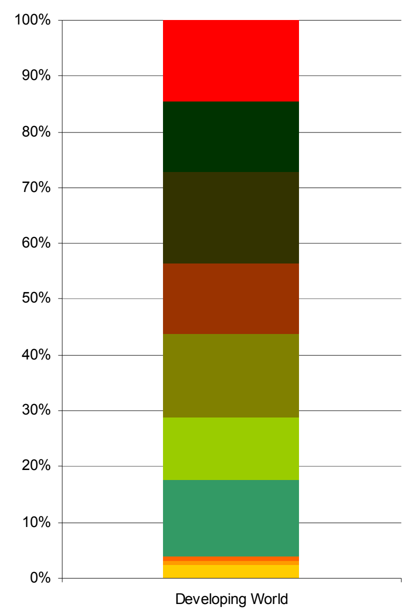
Population estimate 2000 by Thornton et al., 2002, break down to livestock systems

	Easia	Lamerica	NIS	Sasia	SEAsia	SSAfrica	NAWA	**Developing World**
LGA	4,597,071	15,434,504	780,562	18,604,670	-	42,023,944	35,392,977	**116,833,728**
LGH	130,372	10,135,165	4,102	327,764	924,207	16,696,360	180,205	**28,368,175**
LGT	16,964,211	6,636,611	7,437,729	382,653	456,151	3,237,305	531,865	**35,646,525**
MIA	1,418,222	13,815,084	8,762,057	528,300,703	795,568	4,124,304	99,399,683	**656,615,621**
MIH	102,682,564	10,091,361	440,139	206,932,221	203,518,367	127,381	2,303,790	**526,095,823**
MIT	653,977,990	17,460,598	20,537,662	1,195,907	2,431,852	2,177,408	16,379,927	**715,161,344**
MRA	9,893,825	38,804,076	9,169,051	289,599,475	1,399,410	157,092,563	89,130,288	**595,088,688**
MRH	89,037,643	121,726,051	106,717	197,802,454	185,916,851	189,114,552	4,856,990	**788,561,258**
MRT	308,360,832	94,722,113	16,939,572	13,314,672	5,424,473	91,456,254	31,460,831	**591,678,747**
Others	116,842,492	176,722,933	7,903,827	80,884,779	104,502,078	120,921,963	85,756,900	**693,534,972**
Total	1,303,905,222	505,548,496	72,081,418	1,337,345,298	505,368,957	626,972,034	365,393,456	**4,747,584,881**

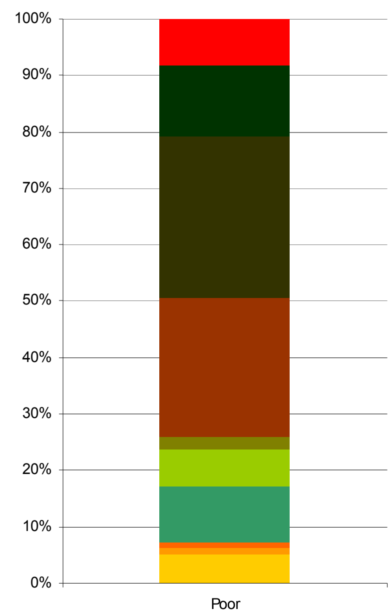
Share of regional population per livestock systems in the developing world



Share of population per livestock system in the developing world



Share of poor livestock keepers per livestock system



Annex Figure Population per livestock system in the developing world for 7 regions [1000 people]. Source: Thornton et al. (2002

8.1. Regional modelling results

Northern Africa and Western Asia

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
NAWA													
Western diet	Monogastric	-	-	-	-	-	-	0,48	0,52	-	-	0,52	0,56
Western diet	BAU	-	-	-	-	-	-	0,49	-	-	-	0,53	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,57	0,61	0,62	0,64	0,62	0,66	0,67	0,69
Baseline diet	BAU	-	-	-	-	0,58	0,61	0,62	0,65	0,62	0,66	0,67	0,70
Baseline diet	Ruminant	-	-	-	-	0,58	0,62	0,63	-	0,63	0,67	0,68	0,70
Less meat diet	Monogastric	-	-	-	0,52	0,59	0,63	0,64	0,66	0,64	0,68	0,69	0,72
Less meat diet	BAU	-	-	0,50	0,52	0,60	0,63	0,64	0,67	0,65	0,68	0,69	0,72
Less meat diet	Ruminant	-	-	0,51	0,53	0,61	0,64	0,65	0,68	0,65	0,69	0,70	0,73
Constant diet	Monogastric	-	-	-	0,55	0,64	0,67	0,68	0,70	0,69	0,72	0,73	0,76
Constant diet	BAU	-	-	0,54	0,56	0,64	0,68	0,69	0,71	0,70	0,73	0,74	0,77
Constant diet	Ruminant	-	-	0,54	0,56	0,65	0,68	0,69	0,72	0,70	0,74	0,75	0,77

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
Western diet	Monogastric	-	-	-	-	-	-	1,35	1,69	-	-	1,34	1,68
Western diet	BAU	-	-	-	-	-	-	1,60	-	-	-	1,58	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,51	0,55	0,67	0,88	0,50	0,54	0,66	0,86
Baseline diet	BAU	-	-	-	-	0,61	0,65	0,77	1,00	0,59	0,64	0,76	0,99
Baseline diet	Ruminant	-	-	-	-	0,70	0,75	0,87	-	0,69	0,74	0,86	1,11
Less meat diet	Monogastric	-	-	-	0,71	0,36	0,40	0,51	0,67	0,35	0,38	0,50	0,66
Less meat diet	BAU	-	-	0,67	0,86	0,48	0,51	0,63	0,82	0,46	0,50	0,62	0,81
Less meat diet	Ruminant	-	-	0,78	1,01	0,59	0,63	0,75	0,97	0,58	0,62	0,73	0,96
Constant diet	Monogastric	-	-	-	0,53	0,25	0,27	0,37	0,50	0,23	0,26	0,35	0,48
Constant diet	BAU	-	-	0,50	0,65	0,34	0,37	0,46	0,62	0,32	0,35	0,45	0,60
Constant diet	Ruminant	-	-	0,59	0,77	0,43	0,46	0,55	0,74	0,42	0,45	0,54	0,72

Central Asia and Russia

CARussia													
Western diet	Monogastric	-	-	-	-	-	-	0,92	1,00	-	-	0,97	1,07
Western diet	BAU	-	-	-	-	-	-	0,94	-	-	-	1,00	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,91	0,91	0,96	1,04	0,96	0,95	1,01	1,12
Baseline diet	BAU	-	-	-	-	0,93	0,92	1,00	1,14	1,00	0,96	1,06	1,22
Baseline diet	Ruminant	-	-	-	-	0,95	0,94	1,04	-	1,01	1,00	1,12	1,34
Less meat diet	Monogastric	-	-	-	1,08	1,14	1,12	1,20	1,29	1,22	1,19	1,28	1,38
Less meat diet	BAU	-	-	1,03	1,14	1,16	1,13	1,23	1,35	1,24	1,21	1,31	1,44
Less meat diet	Ruminant	-	-	1,06	1,20	1,18	1,15	1,26	1,42	1,26	1,23	1,35	1,52
Constant diet	Monogastric	-	-	-	1,00	1,00	0,96	1,04	1,17	1,04	1,01	1,12	1,25
Constant diet	BAU	-	-	0,93	1,05	1,00	1,00	1,08	1,25	1,06	1,03	1,16	1,34
Constant diet	Ruminant	-	-	0,95	1,14	1,01	1,00	1,12	1,36	1,09	1,06	1,20	1,45

Western diet	Monogastric	-	-	-	-	-	-	0,02	0,03	-	-	0,02	0,03
Western diet	BAU	-	-	-	-	-	-	0,03	-	-	-	0,03	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,01	0,01	0,02	0,03	0,01	0,01	0,02	0,03
Baseline diet	BAU	-	-	-	-	0,02	0,02	0,03	0,05	0,02	0,02	0,03	0,05
Baseline diet	Ruminant	-	-	-	-	0,03	0,03	0,04	-	0,03	0,03	0,04	0,06
Less meat diet	Monogastric	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	BAU	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	Ruminant	-	-	-	0,00	-	-	-	0,00	-	-	-	-
Constant diet	Monogastric	-	-	-	0,02	-	-	0,01	0,02	-	-	0,00	0,01
Constant diet	BAU	-	-	0,02	0,03	0,00	0,01	0,01	0,03	0,00	0,00	0,01	0,03
Constant diet	Ruminant	-	-	0,02	0,04	0,01	0,01	0,02	0,04	0,01	0,01	0,02	0,04

Decreased self sufficiency
Self sufficiency close to BAU
Increased self sufficiency

Decreased grazing intensity
Grazing intensity similar to BAU
Increased grazing intensity

Southern Asia

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
SAsia													
Western diet	Monogastric	-	-	-	-	-	-	0,87	1,01	-	-	1,01	1,09
Western diet	BAU	-	-	-	-	-	-	0,90	-	-	-	1,04	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,82	0,84	1,04	1,08	0,90	0,90	1,12	1,16
Baseline diet	BAU	-	-	-	-	0,83	0,84	1,06	1,11	0,91	0,91	1,14	1,20
Baseline diet	Ruminant	-	-	-	-	0,83	0,85	1,09	-	0,92	0,92	1,17	1,23
Less meat diet	Monogastric	-	-	-	1,03	0,79	0,81	1,05	1,10	0,86	0,87	1,13	1,19
Less meat diet	BAU	-	-	0,97	1,05	0,80	0,82	1,06	1,13	0,87	0,88	1,15	1,22
Less meat diet	Ruminant	-	-	1,01	1,07	0,80	0,82	1,08	1,15	0,87	0,88	1,17	1,25
Constant diet	Monogastric	-	-	-	1,14	1,01	0,99	1,19	1,23	1,09	1,07	1,28	1,32
Constant diet	BAU	-	-	1,12	1,16	1,01	1,00	1,20	1,24	1,09	1,08	1,29	1,34
Constant diet	Ruminant	-	-	1,13	1,17	1,01	1,00	1,21	1,26	1,09	1,08	1,31	1,36

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
Western diet	Monogastric	-	-	-	-	-	-	3,58	3,72	-	-	3,41	3,55
Western diet	BAU	-	-	-	-	-	-	3,83	-	-	-	3,67	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,14	0,24	2,21	2,30	-	0,08	2,04	2,14
Baseline diet	BAU	-	-	-	-	0,31	0,42	2,53	2,63	0,14	0,25	2,36	2,47
Baseline diet	Ruminant	-	-	-	-	0,47	0,59	2,85	-	0,30	0,42	2,68	2,79
Less meat diet	Monogastric	-	-	-	2,05	0,07	0,16	1,80	1,90	-	-	1,64	1,73
Less meat diet	BAU	-	-	2,12	2,23	0,16	0,27	1,98	2,08	-	0,10	1,81	1,91
Less meat diet	Ruminant	-	-	2,30	2,41	0,26	0,37	2,15	2,26	0,09	0,20	1,98	2,09
Constant diet	Monogastric	-	-	-	0,28	-	-	0,08	0,13	-	-	-	-
Constant diet	BAU	-	-	0,32	0,38	-	-	0,17	0,23	-	-	0,01	0,06
Constant diet	Ruminant	-	-	0,41	0,47	-	-	0,27	0,32	-	-	0,10	0,16

South-Eastern Asia

SEAsia													
Western diet	Monogastric	-	-	-	-	-	-	1,09	1,13	-	-	1,17	1,21
Western diet	BAU	-	-	-	-	-	-	1,09	-	-	-	1,17	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	1,17	1,16	1,23	1,25	1,25	1,24	1,31	1,33
Baseline diet	BAU	-	-	-	-	1,17	1,15	1,23	1,27	1,25	1,23	1,31	1,35
Baseline diet	Ruminant	-	-	-	-	1,16	1,15	1,22	-	1,24	1,23	1,30	1,39
Less meat diet	Monogastric	-	-	-	1,04	1,16	1,15	1,22	1,24	1,24	1,23	1,30	1,32
Less meat diet	BAU	-	-	1,02	1,05	1,16	1,15	1,22	1,24	1,24	1,22	1,30	1,33
Less meat diet	Ruminant	-	-	1,01	1,08	1,14	1,13	1,20	1,27	1,22	1,21	1,28	1,36
Constant diet	Monogastric	-	-	-	1,13	1,28	1,27	1,33	1,34	1,37	1,36	1,41	1,42
Constant diet	BAU	-	-	1,12	1,14	1,28	1,27	1,32	1,34	1,36	1,35	1,41	1,43
Constant diet	Ruminant	-	-	1,11	1,16	1,27	1,26	1,31	1,36	1,35	1,34	1,40	1,45

Western diet	Monogastric	-	-	-	-	-	-	0,40	0,43	-	-	0,39	0,42
Western diet	BAU	-	-	-	-	-	-	0,46	-	-	-	0,45	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,02	0,03	0,17	0,18	0,01	0,02	0,16	0,18
Baseline diet	BAU	-	-	-	-	0,10	0,11	0,39	0,42	0,09	0,10	0,38	0,41
Baseline diet	Ruminant	-	-	-	-	0,21	0,22	0,70	-	0,20	0,21	0,69	0,75
Less meat diet	Monogastric	-	-	-	0,16	0,01	0,01	0,13	0,14	-	0,01	0,12	0,13
Less meat diet	BAU	-	-	0,22	0,23	0,03	0,04	0,20	0,21	0,02	0,03	0,19	0,20
Less meat diet	Ruminant	-	-	0,53	0,57	0,15	0,16	0,51	0,55	0,14	0,15	0,50	0,54
Constant diet	Monogastric	-	-	-	0,04	-	-	0,02	0,02	-	-	0,01	0,01
Constant diet	BAU	-	-	0,11	0,12	-	-	0,09	0,10	-	-	0,08	0,09
Constant diet	Ruminant	-	-	0,30	0,33	0,05	0,06	0,28	0,31	0,05	0,05	0,27	0,30

Decreased self sufficiency
Self sufficiency close to BAU
Increased self sufficiency

Decreased grazing intensity
Grazing intensity similar to BAU
Increased grazing intensity

North America

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
NAmerica													
Western diet	Monogastric	-	-	-	-	-	-	1,51	1,73	-	-	1,63	1,87
Western diet	BAU	-	-	-	-	-	-	1,44	-	-	-	1,56	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	1,24	1,19	1,46	1,68	1,34	1,28	1,58	1,82
Baseline diet	BAU	-	-	-	-	1,16	1,12	1,39	1,77	1,26	1,21	1,50	1,91
Baseline diet	Ruminant	-	-	-	-	1,10	1,06	1,33	-	1,19	1,15	1,43	2,02
Less meat diet	Monogastric	-	-	-	1,64	2,13	2,07	2,34	2,53	2,29	2,23	2,52	2,72
Less meat diet	BAU	-	-	1,46	1,69	2,05	2,00	2,28	2,60	2,21	2,15	2,45	2,79
Less meat diet	Ruminant	-	-	1,42	1,74	1,98	1,93	2,22	2,68	2,13	2,08	2,38	2,87
Constant diet	Monogastric	-	-	-	1,06	1,24	1,19	1,46	1,68	1,34	1,29	1,58	1,82
Constant diet	BAU	-	-	0,93	1,12	1,17	1,12	1,39	1,77	1,26	1,21	1,50	1,91
Constant diet	Ruminant	-	-	0,91	1,19	1,10	1,06	1,33	1,87	1,19	1,15	1,44	2,02

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	Source of meat												
Western diet	Monogastric	-	-	-	-	-	-	0,04	0,10	-	-	0,04	0,10
Western diet	BAU	-	-	-	-	-	-	0,12	-	-	-	0,12	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	-	-	0,06	0,12	-	-	0,06	0,12
Baseline diet	BAU	-	-	-	-	0,04	0,05	0,15	0,26	0,04	0,05	0,14	0,25
Baseline diet	Ruminant	-	-	-	-	0,12	0,14	0,24	-	0,12	0,13	0,23	0,39
Less meat diet	Monogastric	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	BAU	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	Ruminant	-	-	-	0,03	-	-	-	0,02	-	-	-	0,02
Constant diet	Monogastric	-	-	-	0,13	-	-	0,06	0,12	-	-	0,05	0,12
Constant diet	BAU	-	-	0,15	0,26	0,04	0,05	0,14	0,25	0,04	0,05	0,14	0,25
Constant diet	Ruminant	-	-	0,24	0,40	0,12	0,13	0,23	0,39	0,12	0,13	0,23	0,39

Latin America and the Caribbean

LAmerica													
Western diet	Monogastric	-	-	-	-	-	-	1,39	1,45	-	-	1,49	1,56
Western diet	BAU	-	-	-	-	-	-	1,48	-	-	-	1,59	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	1,35	1,30	1,53	1,59	1,44	1,40	1,64	1,70
Baseline diet	BAU	-	-	-	-	1,45	1,41	1,64	1,76	1,55	1,51	1,75	1,88
Baseline diet	Ruminant	-	-	-	-	1,57	1,53	1,76	-	1,68	1,64	1,88	2,10
Less meat diet	Monogastric	-	-	-	1,39	1,65	1,62	1,79	1,84	1,77	1,73	1,91	1,96
Less meat diet	BAU	-	-	1,41	1,48	1,73	1,70	1,86	1,95	1,84	1,81	1,99	2,08
Less meat diet	Ruminant	-	-	1,48	1,59	1,81	1,78	1,94	2,07	1,93	1,90	2,07	2,21
Constant diet	Monogastric	-	-	-	1,32	1,49	1,45	1,68	1,75	1,59	1,55	1,79	1,86
Constant diet	BAU	-	-	1,34	1,45	1,59	1,55	1,78	1,91	1,70	1,66	1,90	2,03
Constant diet	Ruminant	-	-	1,44	1,62	1,70	1,67	1,90	2,11	1,82	1,78	2,02	2,24

Western diet	Monogastric	-	-	-	-	-	-	0,12	0,13	-	-	0,11	0,13
Western diet	BAU	-	-	-	-	-	-	0,24	-	-	-	0,23	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	-	-	0,09	0,10	-	-	0,08	0,09
Baseline diet	BAU	-	-	-	-	-	-	0,20	0,22	-	-	0,19	0,21
Baseline diet	Ruminant	-	-	-	-	0,04	0,04	0,31	-	0,03	0,04	0,31	0,33
Less meat diet	Monogastric	-	-	-	0,03	-	-	-	-	-	-	-	-
Less meat diet	BAU	-	-	0,08	0,09	-	-	0,05	0,06	-	-	0,04	0,05
Less meat diet	Ruminant	-	-	0,14	0,15	-	-	0,11	0,12	-	-	0,10	0,11
Constant diet	Monogastric	-	-	-	0,10	-	-	0,06	0,07	-	-	0,05	0,06
Constant diet	BAU	-	-	0,18	0,19	-	-	0,15	0,16	-	-	0,14	0,15
Constant diet	Ruminant	-	-	0,27	0,29	0,01	0,02	0,24	0,26	0,00	0,01	0,23	0,25

Decreased self sufficiency
Self sufficiency close to BAU
Increased self sufficiency

Decreased grazing intensity
Grazing intensity similar to BAU
Increased grazing intensity

Western Europe

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	**Source of meat**												
WEurope													
Western diet	Monogastric	-	-	-	-	-	-	1,07	1,11	-	-	1,16	1,20
Western diet	BAU	-	-	-	-	-	-	1,19	-	-	-	1,29	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,89	0,88	1,01	1,05	0,94	0,93	1,09	1,14
Baseline diet	BAU	-	-	-	-	0,92	0,91	1,14	1,24	0,98	0,96	1,23	1,33
Baseline diet	Ruminant	-	-	-	-	0,97	0,95	1,31	-	1,05	1,01	1,41	1,64
Less meat diet	Monogastric	-	-	-	1,01	1,38	1,35	1,51	1,54	1,48	1,45	1,63	1,66
Less meat diet	BAU	-	-	1,05	1,10	1,42	1,40	1,60	1,67	1,53	1,50	1,72	1,79
Less meat diet	Ruminant	-	-	1,13	1,21	1,48	1,45	1,72	1,83	1,59	1,56	1,84	1,96
Constant diet	Monogastric	-	-	-	0,77	0,91	0,91	1,05	1,09	0,97	0,95	1,13	1,17
Constant diet	BAU	-	-	0,76	0,83	0,94	0,93	1,17	1,27	1,01	0,98	1,26	1,37
Constant diet	Ruminant	-	-	0,85	1,02	1,00	0,98	1,35	1,56	1,08	1,05	1,46	1,68

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	**Source of meat**												
Western diet	Monogastric	-	-	-	-	-	-	0,17	0,20	-	-	0,16	0,20
Western diet	BAU	-	-	-	-	-	-	0,29	-	-	-	0,29	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	0,07	0,09	0,24	0,29	0,07	0,08	0,24	0,28
Baseline diet	BAU	-	-	-	-	0,22	0,24	0,39	0,46	0,22	0,24	0,38	0,46
Baseline diet	Ruminant	-	-	-	-	0,37	0,40	0,53	-	0,37	0,40	0,53	0,64
Less meat diet	Monogastric	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	BAU	-	-	-	0,02	-	-	-	0,00	-	-	-	-
Less meat diet	Ruminant	-	-	0,04	0,08	-	-	0,03	0,06	-	-	0,02	0,06
Constant diet	Monogastric	-	-	-	0,27	0,05	0,07	0,21	0,25	0,05	0,06	0,21	0,25
Constant diet	BAU	-	-	0,37	0,44	0,19	0,22	0,35	0,42	0,19	0,21	0,35	0,42
Constant diet	Ruminant	-	-	0,51	0,61	0,34	0,36	0,49	0,59	0,33	0,36	0,49	0,59

Eastern Europe

EEurope													
Western diet	Monogastric	-	-	-	-	-	-	1,28	1,38	-	-	1,37	1,48
Western diet	BAU	-	-	-	-	-	-	1,26	-	-	-	1,35	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	1,32	1,27	1,39	1,51	1,42	1,37	1,49	1,61
Baseline diet	BAU	-	-	-	-	1,27	1,22	1,38	1,62	1,36	1,31	1,48	1,73
Baseline diet	Ruminant	-	-	-	-	1,21	1,17	1,38	-	1,30	1,26	1,48	1,89
Less meat diet	Monogastric	-	-	-	1,30	1,75	1,71	1,82	1,92	1,87	1,83	1,94	2,05
Less meat diet	BAU	-	-	1,21	1,36	1,69	1,65	1,81	2,01	1,81	1,76	1,93	2,14
Less meat diet	Ruminant	-	-	1,20	1,45	1,63	1,59	1,79	2,13	1,75	1,70	1,91	2,26
Constant diet	Monogastric	-	-	-	1,08	1,44	1,39	1,51	1,63	1,54	1,49	1,62	1,74
Constant diet	BAU	-	-	1,00	1,16	1,37	1,32	1,49	1,73	1,47	1,42	1,60	1,85
Constant diet	Ruminant	-	-	1,00	1,26	1,31	1,26	1,48	1,88	1,40	1,36	1,58	2,00

Western diet	Monogastric	-	-	-	-	-	-	0,03	0,10	-	-	0,03	0,09
Western diet	BAU	-	-	-	-	-	-	0,16	-	-	-	0,16	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	-	-	0,03	0,09	-	-	0,02	0,09
Baseline diet	BAU	-	-	-	-	0,04	0,06	0,16	0,27	0,04	0,05	0,16	0,27
Baseline diet	Ruminant	-	-	-	-	0,13	0,15	0,29	-	0,12	0,14	0,29	0,45
Less meat diet	Monogastric	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	BAU	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	Ruminant	-	-	-	0,08	-	-	-	0,07	-	-	-	0,07
Constant diet	Monogastric	-	-	-	0,03	-	-	-	0,01	-	-	-	0,01
Constant diet	BAU	-	-	0,08	0,17	-	-	0,06	0,16	-	-	0,06	0,15
Constant diet	Ruminant	-	-	0,18	0,31	0,04	0,05	0,16	0,30	0,03	0,05	0,16	0,30

- Decreased self sufficiency
- Self sufficiency close to BAU
- Increased self sufficiency
- Decreased grazing intensity
- Grazing intensity similar to BAU
- Increased grazing intensity

Oceania

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	**Source of meat**												
Oceania													
Western diet	Monogastric	-	-	-	-	-	-	1,50	1,53	-	-	1,61	1,65
Western diet	BAU	-	-	-	-	-	-	1,71	-	-	-	1,83	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	1,21	1,16	1,61	1,64	1,31	1,25	1,73	1,76
Baseline diet	BAU	-	-	-	-	1,31	1,26	1,85	1,91	1,41	1,36	1,98	2,05
Baseline diet	Ruminant	-	-	-	-	1,44	1,39	2,21	-	1,55	1,50	2,36	2,49
Less meat diet	Monogastric	-	-	-	1,76	1,76	1,72	2,06	2,08	1,89	1,84	2,20	2,22
Less meat diet	BAU	-	-	1,87	1,91	1,84	1,80	2,20	2,24	1,97	1,93	2,35	2,39
Less meat diet	Ruminant	-	-	2,04	2,09	1,94	1,90	2,39	2,45	2,07	2,04	2,55	2,61
Constant diet	Monogastric	-	-	-	1,48	1,32	1,26	1,73	1,76	1,42	1,36	1,85	1,89
Constant diet	BAU	-	-	1,66	1,72	1,42	1,36	1,97	2,03	1,52	1,47	2,10	2,17
Constant diet	Ruminant	-	-	1,98	2,10	1,55	1,50	2,33	2,45	1,66	1,61	2,48	2,61

	Yields	Low	Low	Low	Low	Conv	Conv	Conv	Conv	High	High	High	High
	Livestock diet	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT	INT	INT + Roam	TREND	EXT
Diet	**Source of meat**												
Western diet	Monogastric	-	-	-	-	-	-	0,03	0,03	-	-	0,03	0,03
Western diet	BAU	-	-	-	-	-	-	0,05	-	-	-	0,05	-
Western diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Baseline diet	Monogastric	-	-	-	-	-	-	0,03	0,03	-	-	0,03	0,03
Baseline diet	BAU	-	-	-	-	-	0,00	0,05	0,05	-	0,00	0,05	0,05
Baseline diet	Ruminant	-	-	-	-	0,01	0,02	0,07	-	0,01	0,02	0,07	0,07
Less meat diet	Monogastric	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	BAU	-	-	-	-	-	-	-	-	-	-	-	-
Less meat diet	Ruminant	-	-	-	-	-	-	-	-	-	-	-	-
Constant diet	Monogastric	-	-	-	0,02	-	-	0,02	0,02	-	-	0,02	0,02
Constant diet	BAU	-	-	0,04	0,04	-	-	0,04	0,04	-	-	0,04	0,04
Constant diet	Ruminant	-	-	0,06	0,06	0,01	0,01	0,06	0,06	0,01	0,01	0,06	0,06

Decreased self sufficiency
Self sufficiency close to BAU
Increased self sufficiency

Decreased grazing intensity
Grazing intensity similar to BAU
Increased grazing intensity

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