Chapter 14
Systemic Feedbacks in Global Land Use

Helmut Haberl, Karl-Heinz Erb, Thomas Kastner, Christian Lauk and Andreas Mayer

Abstract Land is a key resource, not only for human societies but also for all organisms—animals, plants and microorganisms—that inhabit terrestrial ecosystems worldwide. Humans use land for at least three purposes: resource supply, waste repository and living space (i.e., the area required for production, consumption, transport, recreation and many other activities). Land use involves the 'colonization of ecosystems', that is, purposive interventions into terrestrial ecosystems that aim to support these functions, usually by transforming natural into managed ecosystems (e.g., agro-ecosystems, managed forests, urban systems). Increasingly, land use also aims at other services, such as the conservation of habitats, species or ecosystems or increased carbon sequestration. Maximization of one function, such as biomass supply, often affects other functions, such as carbon sequestration or conservation. Along with the growth of the world population and its per-capita consumption, trade-offs among different functions are becoming more important. A particularly relevant example is the trade-off between food and fuel that has become apparent in the last few years as policies promoting bioenergy on agricultural lands have gained momentum. Although some of these trade-offs can only be mitigated but not completely avoided (e.g., biomass production requires

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limited resources such as productive area and water), a sociometabolic approach can help identify potential synergies. For example, the use of wastes, by-products and residues ('cascade utilization') may help to increase biomass use efficiency and generate several outputs without resulting in resource competition. This chapter discusses such trade-offs and synergies in global land use with a view toward issues of resource supply (mainly food and energy) as well as various ecological conservation aspects (e.g., biodiversity conservation, carbon sequestration and environmentally less-demanding agricultural technologies).

Keywords Socioeconomic metabolism · Biomass flows · Land-use competition · Cascade utilization of biomass · Carbon sequestration

14.1 Introduction

In Ecology, the word 'colonization' is used when a species succeeds in extending its range into previously uninhabited terrain. In that sense, Homo sapiens is one of the world's most successful species, inhabiting almost all the planet's lands. Humans now use approximately three-quarters of the global land area,[1] more or less intensively, for living space, cropland, grazing and forestry. Only one-quarter of the earth's land is classified as (almost) natural (Ellis et al. 2010). Most of this land area may be highly valuable ecologically, but its biological productivity is low because it is dry or cold (e.g., deserts and arctic or alpine tundra). The remnants of natural forests, covering perhaps 5–7 % of the global land area, are among the few biologically productive but still largely pristine ecosystems (Erb et al. 2007).

Hence, on the vast majority of the earth's terrestrial surface, patterns, dynamics and functions of land systems emerge through intensive, recursive and complex interactions between natural and socioeconomic processes (Turner et al. 2007). Cultural landscapes are shaped by interactions between natural factors (such as geomorphology, landforms, climate and biotic communities) and socioeconomic activities (such as agriculture, forestry, settlement and infrastructure development and energy use). The analysis of cultural landscapes is a genuinely interdisciplinary endeavor and is a core research area of Social Ecology (Fischer-Kowalski et al. 1997).

With few exceptions, human societies organize land according to their needs and wants, namely, for the delivery of provisioning, regulating or cultural ecosystem services (Braat and de Groot 2012). The ecological notion of colonization is insufficient to capture this process. The colonization concept developed in Social Ecology therefore also encompasses purposive human interventions into natural

[1]In this chapter, we discuss a land surface of approximately 130 million km²; that is, all of the earth's land outside Greenland and Antarctica.

systems—in this case, terrestrial ecosystems—to optimize them in terms of their utility for human society. Colonization may transform ecosystems, which happens when forests are converted to croplands, meadows or pastures. However, colonization may also affect populations and organisms, such as through the breeding of crops and animals, and it may affect genomes directly through genetic engineering (Fischer-Kowalski et al. 1997). Hence, humans not only profit from ecosystem services delivered spontaneously by ecosystems but also colonize these ecosystems to increase or alter their service delivery—a process usually denoted as 'land use'. Land may be used with very different intensities, ranging from small interventions to strong modifications of ecosystems. Land-use intensity has three dimensions: socioeconomic inputs to the land, outputs from the land to human society and changes in the integrated socioecological system (see Chap. 4), as measured using the 'human appropriation of net primary production' (HANPP) approach (see Method Précis on Human Appropriation of Net Primary Production and Chap. 17 in this volume).

Because global land is finite and predominantly human-used (particularly the naturally fertile regions), almost any extension of area use for one purpose implies a reduction in the available area for other functions or services. To some extent, land can serve more than one function at a time ('multifunctionality') . For example, extensively used farmland can deliver food while also supporting valuable biotic communities, hence contributing to the conservation of biodiversity. Similarly, the use of by-product flows may result in synergies; increases in food crop production may raise by-product flows that can be used to feed livestock or for energy production. In many cases, however, maximization of one function (e.g., crop production) entails a reduction of other functions, such as biodiversity conservation, water retention capacity or carbon sequestration. In most cases, the maximization of one ecosystem service reduces others, resulting in trade-offs (Braat and de Groot 2012).

When different social groups profit from different services or suffer from adverse effects that result from the maximization of one specific product, land-use competition or even conflicts may arise. The extension of area required for food production may reduce the area available for carbon sequestration, biodiversity conservation or bioenergy production. A switch to organic agriculture has many positive ecological effects, including reduced pressure from pesticides and chemical fertilizers, improved soil quality and higher on-site biodiversity (IAASTD 2009), but it also reduces yields (Seufert et al. 2012). If demand remains the same, this implies increased demand for cropland and grazing areas, which may result in increased pressure on other ecologically valuable natural or semi-natural areas (Burney et al. 2010). The results of increases in land-use intensity resulting from mechanization, irrigation, fertilization and pesticides and from high-yield crop varieties and livestock breeds are also ambivalent; although they contribute to environmental pressures and problems such as inhumane animal husbandry systems, nutrient leaching, soil erosion, biodiversity loss and the toxic effects of pesticides (IAASTD 2009), they may reduce the area demand of agriculture and perhaps even reduce greenhouse gas (GHG) emissions due to land-use change

(Burney et al. 2010). In many industrialized countries, the emergence of substantial carbon sinks in biota and soils was made possible through massive increases in agricultural productivity per unit area (see Chap. 20). However, increased land-use intensity is no panacea, not only because of its potential ecological costs but also because it may induce socioeconomic feedbacks, the so-called 'rebound' effect: increased efficiency in production may result in rising consumption. Increased land-use intensity may even be a precondition for the adoption of resource-intensive consumption patterns such as increased consumption of meat and other animal products (Lambin and Meyfroidt 2011).

In this chapter, we discuss several important trade-offs and synergies related to global land use from a socioecological perspective to show how the concepts of metabolism and colonization can help us better understand systemic feedbacks—trade-offs as well as synergies—between different possible future changes in food consumption, cropland yields and livestock feeding efficiency.

14.2 Agriculture and Food Scenarios for 2050

The provision of sufficient amounts of nutritionally adequate food is one of the most important functions of global land use. Although biomass is used for additional purposes (fiber, energy), food supply is thought to occupy nearly half the earth's land area, that is, most of the area used as cropland and grazing land (Erb et al. 2007). The continuing growth of the human population and economic output (gross domestic product, GDP) are generally expected to result in a massive growth of food consumption, in terms of both total calories and the fraction of its most resource-demanding component: animal products (meat, milk, eggs). The UN Food and Agricultural Organization (FAO 2006) foresees a 70 % growth in the demand for agricultural products by 2050. Other studies even expect a doubling of global food demand (Tilman et al. 2011).

14.2.1 Dietary Change

In the last few decades, increased wealth was almost inextricably linked with increased consumption of animal products (meat, milk, eggs), sugar and oils and with reduced consumption of cereals, potatoes, rice and other staples (Erb et al. 2009). Future deviations from this trend are conceivable, but their likelihood is difficult to assess. There might be a reduced consumption of animal products in rich countries due to health concerns or greater environmental consciousness, but it is just as likely that currently undernourished regions might adopt European or US-American food consumption habits faster than foreseen by the FAO. To estimate the range of possible future food demand, we define several variants of possible future diets, the adoption of which would have massive consequences

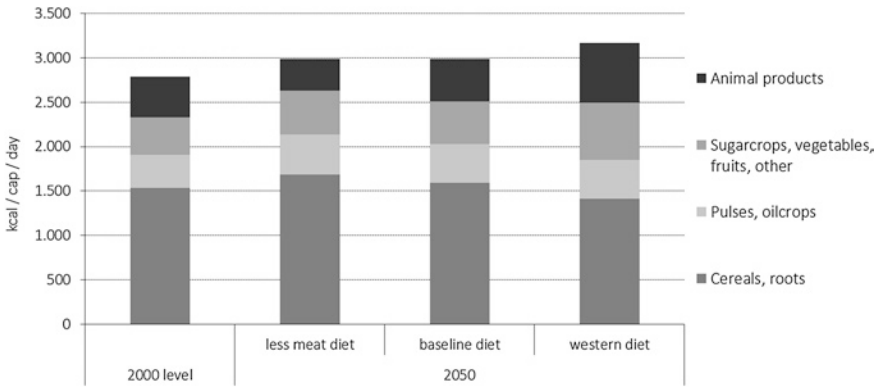

Fig. 14.1 Global calorific intake per capita for main food categories in 2000 and variants for 2050. (Source: Erb et al. 2012)

for future land requirements for food supply. In particular, the share of animal products in diets has enormous implications for land demand. In the year 2000, approximately 60 % of all biomass harvested and used by humans was required to feed livestock (Krausmann et al. 2008).

Figure 14.1 compares three possible future diet variants with the level and composition of global average food intake in the year 2000 (Erb et al. 2012). The 'baseline diet' is an extrapolation of current trends closely resembling FAO forecasts (FAO 2006). The 'less meat diet' assumes the same global average per capita calorie supply but a reduced share of animal products. The 'western diet' represents a scenario that assumes that poorer regions will catch up with Western European and US-American food habits faster than assumed in the baseline diet.

All these diet variants are nutritionally sufficient; they supply the world population in the year 2050 with sufficient calories and protein. In the 'less meat diet', protein deficiency is avoided through an assumed increase in the intake of protein-rich plant foods such as beans, lentils, peas and soybeans.[2]

14.2.2 Crop Yields

In an aggregate view, two parameters are most important on the supply side: (1) yields per unit area per year and (2) the conversion efficiency with which livestock converts feedstuff into meat, milk and eggs. Both parameters vary enormously

[2]We also analyzed variants of the 'baseline diet' by tweaking the production of animal products (a) toward pigs and poultry (+50 %, milk and ruminant meat reduced accordingly) and (b) toward ruminants by reducing pig and poultry products by 50 % and increasing ruminants accordingly. In both cases, the total consumption of animal products was assumed to remain the same as in the baseline.

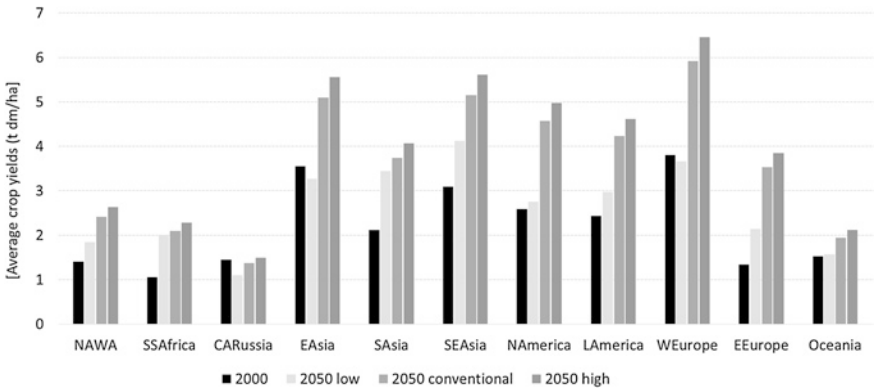

Fig. 14.2 Average crop yields in 2000 and 2050 for three different variants (see text) in a regional breakdown. Values are metric tons dry matter per hectare and per year. (Source: Erb et al. 2009)

among regions, crops and livestock species, and they strongly depend on agricultural technologies and management such as fertilization, soil management, breeding and livestock rearing conditions and herd management.

The FAO expects cropland yields to grow by more than 50 % globally by 2050. Approximately four-fifths of the projected growth in agricultural production is assumed to be the result of increased yields on existing croplands (FAO 2006). The 'Global Orchestration' scenario (Millennium Ecosystem Assessment 2005) assumes an even stronger growth of yields. Switching to organic agriculture reduces yields significantly. Although the yield of an organic wheat field may be nearly as high as that of a conventional one (Seufert et al. 2012), organic agriculture relies on intercrops and fallow to regenerate the soil nutrient pools and maintain soil fertility; over the entire crop rotation cycle, intercrops and fallows reduce yields considerably. According to a literature review (Erb et al. 2009), yields of organic agriculture are approximately 40 % lower over the entire crop rotation period than those of conventional, highly intensive agriculture. Based on these considerations, we derived three yield variants for the year 2050, displayed in Fig. 14.2, and compared them with the yield level achieved in the year 2000 in the respective world region.

The 'conventional' yield variant is based on FAO forecasts (FAO 2006). The 'high' variant was derived from the highest scenario within the Millennium Ecosystem Assessment (2005), which assumes 9 % higher yields than FAO in 2050. Both result in considerable yield increases in almost all world regions (Fig. 14.2). The 'low' variant assumes yields that could be achieved by fully switching to organic agriculture (Erb et al. 2009). The low-yield variant allows for modest increases in crop yields in some regions where yields are currently very poor (e.g., Sub-Saharan Africa and Asian regions, see Fig. 14.2): even organic agriculture can surpass yields achieved with traditional technologies prevailing in these regions. Yield reductions were only assumed for the fraction of cropland cultivated using intensive high-input methods, which is low in many regions.

14.2.3 Animal Husbandry: Feeding Efficiency

Measuring the efficiency with which livestock converts feedstuff into products is a complex endeavor. Conventionally, efficiency is input divided by output, but neither is easy to capture. The question of how 'products' or 'outputs' of livestock should be defined or what is even considered a product is less trivial than it sounds. In most industrial societies, the provision of animal-derived food such as meat, milk and eggs is seen as the dominant output of animal husbandry. Of course, dogs or cats serving as companions and horses serving for leisure riding also play a role.[3] In preindustrial settings, other outputs or even services may be very important, such as the work force of animals (draft animals), their importance as an economic buffer in bad times, their relevance as a status symbol and, not least, their contribution to the nutrient cycle, which can be harnessed by feeding animals with feed from grasslands or even forests and fertilizing the most intensively cropped areas with their manure. In industrial societies, the internal combustion engine and electric motors have replaced draft animals; cars and electronic gadgets have replaced livestock as symbols of wealth and power; and synthetic fertilizers have greatly reduced the importance of livestock in the (short-term) maintenance of soil fertility, at least in many intensively cropped regions. The services pets provide are difficult to name and quantify.

Measuring input is also not straightforward. Of course, it is possible to calculate the energy equivalent of feed (or the amount of protein it contains), but the resulting numbers are not always easy to interpret. For example, ruminants (cattle, sheep and goats) can digest roughage unsuitable for consumption by other species. The low digestibility of roughage results in a low conversion efficiency of feed to products, but the ability to digest roughage also means that these animals can dwell on resources not accessible to other species, especially humans. In contrast to species with a much higher 'feeding efficiency' in terms of pure energy input-output ratios (e.g., pigs and poultry), these animals do not compete with humans for food, and they allow the use of land that cannot (or at least not easily) be used for food production through cropping.

Moreover, the feeding efficiency of ruminants, measured as a calorie input/output ratio, improves if they are fed more easily digestible, high-calorie (high-protein) feeds. Hence, improved feeding efficiency depends, at least to some extent, on the increased use of high-quality feeds. These feeds, however, increase the competition between humans and livestock for food and area, except if livestock is fed on wastes not deemed acceptable for human consumption. The optimization of herd dynamics is another important determinant of feeding efficiency. If animal populations are optimized for meat output, animals are slaughtered when their

[3]Pets could not be modeled explicitly due to a lack of data. For the year 2000, their feed intake is included in the animal production/consumption data. Implicitly, this means they are scaled up/downward with changes assumed in animal product consumption in the different diet variants.

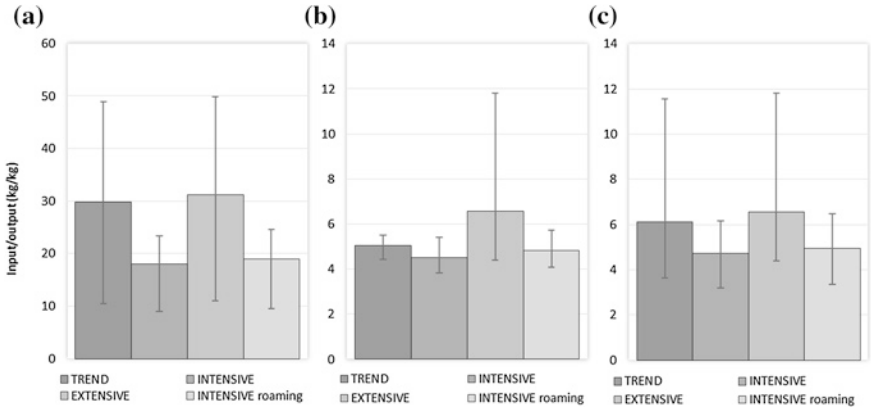

Fig. 14.3 Variants of global livestock feeding efficiencies in the year 2050: **a** ruminant meat, **b** monogastric species and **c** milk, butter and other dairy products. Values are unweighted arithmetic mean of regions. Whiskers indicate the maxima and minima of regional factors. Unit: dimensionless (kg dry matter/kg dry matter). Note that the scale of **a** differs from that of **b** and **c**. (Data Source: Erb et al. 2012)

body weight growth plateaus; continuing to feed them once the growth of their muscle mass declines would be a waste of feed. If, however, animals serve more purposes than just food production or if they are kept in regions with abundant grazing area, such 'optimization' may not be a primary target of the farmer, and feeding efficiencies in terms of input/output ratios can thus be surprisingly low (Thornton 2010).

The variants of feeding efficiency underlying our calculations are described in Fig. 14.3. They are based on the analysis of feed input-output ratios in 11 world regions in the last few decades (Bouwman et al. 2005; Erb et al. 2012; Krausmann et al. 2008). The feeding efficiencies reported in Fig. 14.3 were defined as the ratio of feed requirements of all livestock (including working animals and animals for reproduction) per unit of output of usable animal biomass, both measured as dry matter biomass. These variants reflect not only differences in management but also different strategies for feeding domesticated animals. The 'trend' variant is developed by extrapolating a forecast (Bouwman et al. 2005) for 2030–2050. The 'intensive' variant assumes intensive stable-kept rearing of animals using optimized herd management with a higher share of crop-based feed and accordingly reduced roughage demand. The 'intensive, roaming' variant is based on the same optimization of feeding and herd management but assumes that animals are allowed to roam according to standards of humane livestock rearing, which results in higher area demand and reduced feeding efficiency. The 'extensive' variant assumes a reduced share of grain-based feeds and, accordingly, higher roughage demand.

Figure 14.3 shows that feeding efficiencies differ quite strongly among variants and regions by factors of up to 5 for ruminant meat and by greater than 3 for meat

of pigs, chicken and other monogastric species and for milk and other dairy products. Feeding efficiencies differ strongly between intensive and extensive variants, especially for ruminant meat, whereas animals managed otherwise intensively but allowed to roam are only slightly less 'efficient' than animals kept in stables. In other words, adopting humane livestock rearing conditions results in only minor losses in feeding efficiency (Erb et al. 2009).

14.2.4 Biomass Flows and Land Use 2050

Based on the assumptions explained above, we estimated the area required for global food supply in 2050 using the biomass-balance model BioBaM (Erb et al. 2009, 2012). BioBaM allows global biomass flows to be traced from production to consumption. It also allows feedbacks among changes in food demand, production technologies (yields, feeding efficiency) and land requirements to be assessed. It calculates the effects of assumed changes (called 'variants') in diets, yields and livestock feeding efficiency on the demand of cropland area and on the intensity with which grazing areas are exploited. Each specific combination of variants is denoted as a 'scenario'.

BioBaM is a purely biophysical biomass-balance model built on a global database that consistently integrates the global land-use pattern in the year 2000 (Erb et al. 2007) with a biomass balance for the same year (Krausmann et al. 2008). It contains neither dynamic simulation nor optimization algorithms, and it allows the transparent implementation of different assumptions and assessments of their consequences (Erb et al. 2009, 2012).[4] To derive estimates for the year 2050, land-use and biomass flow data for the year 2000 are modified to reflect 2000/2050 changes based on exogenous assumptions, the most important of which are discussed in the preceding sections. BioBaM determines whether any specific scenario (i.e., combination of variants) is 'feasible'. A scenario is classified as feasible if sufficient cropland and grazing land is available to produce the required volume of food products given the assumed yields and feeding efficiencies (within an uncertainty range of ±5 %).[5]

Cropland availability, which is used to decide whether the demand for cropland area can be met in each scenario, is derived from information on the developments of yield, cropping index and harvested area from FAO (2006). Because we are interested in a large option space, we doubled the cropland area increase estimated

[4]BioBaM distinguishes 11 world regions, seven crop aggregates and two different animal production systems (ruminants, monogastrics). The results can be disaggregated in geographic information system (GIS) grids with a five-minute geographic resolution (ca. 10 km at the equator) based on data by Erb et al. (2007).

[5]In all scenarios, urban and infrastructure areas are assumed to grow by +24 % until 2050. Cropland area demand is calculated from food demand according to the variants of yields and feeding efficiencies. The world population in 2050 is assumed to be nine billion.

by FAO (2006) using consistency checks as described in Erb et al. (2009). The expansion of cropland between 2000 and 2050 was thus +19 % on global average (in contrast to +9 % estimated by FAO 2006), with huge regional variations (e.g., +42 % in Latin America, +56 % in Sub-Saharan Africa). The cropland expansion is assumed to occur only on grazing land of high quality. For our scenario analysis, we assumed that cropland expansion does not result in deforestation; in other words, the analysis does not include trade-offs between forest protection and agricultural developments. Rather, it is assumed that cropland expansion reduces the area of grazing land and would—if all parameters were kept constant (e.g., feed demand)—result in an increase of grazing intensity (the same harvest volumes on smaller areas). The feasibility of scenarios related to grazing intensity is evaluated below.

Grazing land, which occupies a much larger area than cropland globally, is a complex issue (Chap. 13). Grazing land is an umbrella term for many different land categories that can potentially be used for grazing or mowing (hay, silage) with very different intensities. Some of this land is used intensively and is even irrigated and fertilized. This category also includes shrubland, tundra, mountains and other semi-natural lands used extensively or even intermittently for grazing. Different qualities of grazing land are reflected in a subdivision into four grazing land quality classes, where 1 is the most and 4 the least suitable quality class (Erb et al. 2007). For each of these quality classes, an upper limit of the percentage of aboveground net primary production (NPP) that can be grazed can be specified, thus allowing sustainability limits to be estimated for grazing pressure. To evaluate the feasibility of the scenarios, we assumed maximum grazing intensities of 75, 55, 40 and 20 % of NPP for grazing land of quality classes 1–4, respectively. It can be assumed that grazing land class 1 is potentially suitable for cropping (Erb et al. 2009), especially less-demanding energy crops such as herbaceous (e.g., Miscanthus sinensis or switchgrass) or woody (e.g., short-rotation coppice) second-generation energy plants (Haberl et al. 2011).

To compare the different scenarios, we calculated the area potentially available for purposes other than food production as follows. For all scenarios classified as feasible (see above), we calculated the area of cropland required to meet food/feed demand according to the yield level assumed in the scenario and grazing land in quality class 1 required to meet forage demand under the respective assumptions. We assumed that grazing and mowing were intensified up to the maximum sustainable use of the respective land area; that is, we assumed that the required roughage is extracted in a manner that minimizes the area required for grazing or mowing. In other words, we adopted a food-first approach to calculate the smallest possible area in each region's grazing land of quality class 1 that would suffice to cover roughage demand allocated to that quality class in each scenario. The area of cropland and grazing land (class 1) required for food supply was subtracted from the area of cropland and class 1 grazing land, revealing an upper limit for the area of cropland or grazing land that might be available for other purposes, such as energy crop production, the planting of new forests to sequester carbon or the establishment of nature conservation areas. Only grazing land quality class 1

is assumed to be potentially suitable for cropping at a reasonable level of investment (Coelho et al. 2012). The results are shown in Fig. 14.4. Note that 'baseline' means that diets, yields and feeding efficiencies develop according to FAO forecasts, not that the grazing land intensification assumed in calculating area demand will necessarily occur. In the absence of targeted policies or economic incentives, it seems unlikely that such an intensification of grazing areas would happen, and it is an open question whether such an intensification would be desirable or what it would cost to achieve it. The results may also be interpreted as an indication of grazing pressure; low area availability indicates high grazing pressure and vice versa.

Potentially available land is inversely related to the food system's land demand: the smaller the area of potentially available land, the higher the land demand of food production (assuming a standardized, high level of grazing pressure) or the pressure on grazing land. Figure 14.4 can hence be interpreted in terms of food-related land demand. It shows systemic interrelations and trade-offs among

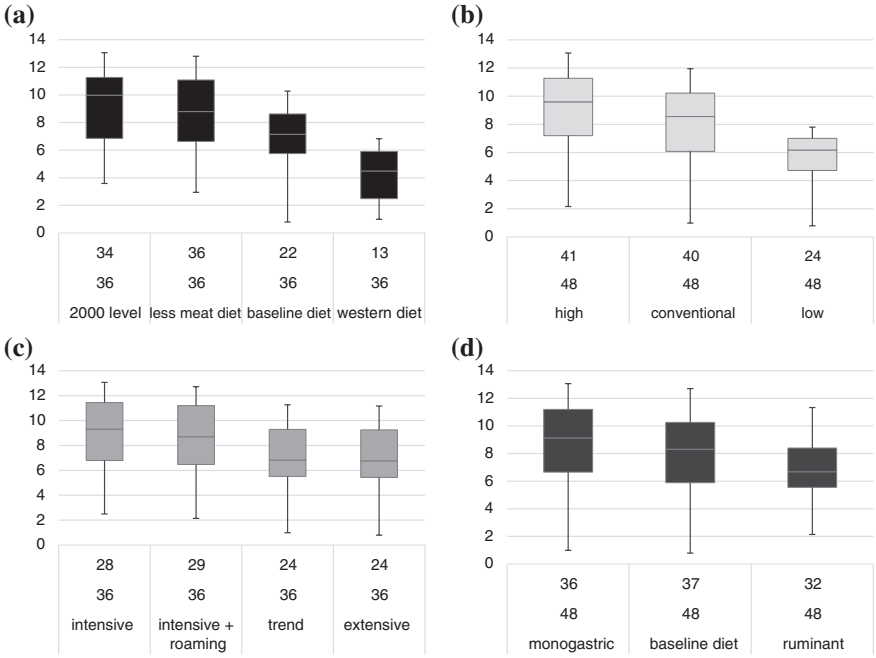

Fig. 14.4 Box plots showing the area potentially available in the year 2050 for purposes other than food production on good-quality land (i.e., cropland and high-quality grassland) in all scenarios classified as feasible; y-axis unit: million km^2. **a** Diet variants, **b** crop yield variants, **c** variants of livestock feeding efficiencies, **d** baseline diet tweaked toward higher shares of products from monogastrics or from ruminants. *Whiskers* show the full ranges of all feasible scenarios, *boxes* show quartiles (Q), i.e., the range from Q1 to Q3, and the *horizontal line* in each box shows the median (Q2). The numbers below the *box plots* indicate the number of all scenarios in the respective variants (*below*) and the number of 'feasible' scenarios (*above*)

different assumed future changes in the food and agriculture system. As expected, higher food demand, lower yields, lower feeding efficiencies and a higher share of ruminant products result in higher pressures of food production on the earth's land surface.

The choice of ruminant-based vs. monogastric-based animal products substantially affects area requirements of food production. The reason is the lower energy efficiency of ruminants compared to monogastrics, which is related to the much lower feed value of their diet (roughage). However, a higher fraction of monogastric products also results in more cropland, that is, more intensive land use. This can lead to the abandonment of ecologically valuable, high-biodiversity extensive grazing systems that store much carbon in the soil. Moreover, not all areas grazed by ruminants are suitable for cropping. Hence, these numbers need to be interpreted cautiously to avoid flawed conclusions or flawed policy recommendations.

14.3 Trade-Offs and Synergies

14.3.1 Organic Agriculture Versus Land-Sparing Intensive Agriculture

The ecological advantages of organic agriculture are substantial and include reduced loss of organic materials in the soil, better soil fertility, lower use of toxic chemicals such as pesticides, reduced leaching of nitrates and other plant nutrients and higher on-farm biodiversity (IAASTD 2009; Maeder et al. 2002). However, lower yields per unit area per year translate to an increase in area demand. Although an organic crop field may reach nearly the same yield level as a crop field cultivated with intensive industrialized farming methods, the overall yield of organic agriculture is substantially lower due to the additional area needed for crop rotation and the intercropping schemes required to replenish soil fertility (Guzman et al. 2011). This is by no means a trivial issue. Globally, approximately one in seven persons is malnourished (approximately as many are overfed; Godfray et al. 2010). Since 1950, agricultural production has grown faster than the population, resulting in improved nutrition and a reduction in both the fraction and the absolute number of malnourished people in the world (FAO 2013); whereas 26 % of the world population went hungry in the 1960s, this fraction has dropped to 12 % today. Most—probably more than three-quarters—of the increased agricultural production was achieved through intensification; the expansion of farmland played a much smaller role. The prolongation of these trends until 2050 may be impossible to achieve with organic agriculture.

Could organic agriculture feed the world? Our scenario calculations suggest it might be able to, but only if the 'less meat' diet is adopted, and even then, not for all variants of feeding efficiency. Moreover, at any given level of product supply, the area required for global food supply is larger when only organic agriculture

is used compared to stronger yields increases based on industrialized farming methods. Larger area demand bears substantial ecological costs: it increases the pressure to extend farmland beyond its current boundaries, which usually results in deforestation and loss of other natural or semi-natural areas and leaves less area for biodiversity conservation, carbon sequestration and bioenergy production (Smith et al. 2013).

There are additional systemic feedbacks, such as the following:

- The biodiversity of areas farmed according to standards of organic agriculture is higher than that of conventional industrial farming. However, if organic farming requires more area, it may leave less area for biodiversity conservation and, hence, result in stronger pressures on biodiversity outside food farming areas. Whether 'land sharing' or 'land sparing' puts less pressure on biodiversity is a complex and unresolved question (Butsic et al. 2012).
- Organically grown food is usually more expensive than products from conventional farming. On the one hand, this would hamper the supply of sufficient food to poorer parts of the population as more widespread adoption of organic agriculture would result in an upward trend of food prices. This could lead to more hunger and malnutrition. On the other hand, the fact that products of conventional agriculture are cheaper may result in additional demand related to rebound effects that stimulate ecologically more demanding consumption patterns with a higher land demand (Lambin and Meyfroidt 2011). Ceteris paribus assumptions are, hence, of questionable value.

The nagging question remains whether the yield forecasts in the 'trend' variant, and even more so, the 'high' variant, are realistic. In some world regions, the growth of yields is already slowing. Soil degradation may hamper further yield growth in intensively used regions (Winiwarter and Gerzabeck 2012). Some strategies for yield improvements, such as improved harvest indices, may be about to reach physiological limits. In modern wheat cultivars, for example, the fraction of total aboveground biomass allocated to the commercial crop has already reached 40–60 % (Krausmann et al. 2008). It does not seem likely that plants could grow and remain productive and resilient with an even lower share of plant tissue allocated to leaves and stems.

14.3.2 Bioenergy, Carbon Sinks and Conservation Areas

The differences in potential area availability shown in Fig. 14.4 are by no means trivial. For example, the 4 million km^2 difference between the less meat diet and that of the western diet (Fig. 14.4a) is more than one-quarter of current global cropland. If planted with energy crops with a relatively modest assumed primary energy yield of 20 MJ/m^2/year (megajoules per square meter per year; 1 MJ = 10^6 J), this area would deliver 80 EJ/year (exajoules per year; 1 EJ = 10^{18} J) of primary bioenergy, or approximately 15 % of current global

technical primary energy consumption, which would be a substantial contribution to the global energy supply. Hence, the magnitude of the bioenergy potential strongly depends on the choice of diet, the food crop yields achieved and the livestock feeding efficiencies, among many other factors (Coelho et al. 2012).

Even if productive land areas could be made available, other systemic feedbacks need to be considered before concluding that bioenergy is the best option. First, the full GHG costs of implementing such large-scale bioenergy schemes are unknown. For the area to become available, the intensification of livestock grazing is required, as described above. Such intensification would likely affect the amount of carbon stored in these areas because extensive grazing land stores far more carbon in soils than intensively used grasslands. Moreover, cultivating bioenergy plants would entail ploughing up substantial land areas, which could also result in carbon loss, although this effect depends on the energy crop chosen. Short-rotation coppice and perennial grasses can provide bioenergy while sequestering carbon when they are grown on soils that had been used for cropping, particularly when grown on degraded lands (Coelho et al. 2012), but whether this also applies when they are planted on lands that had previously been extensively grazed is unclear.

Second, using the land for bioenergy means it is unavailable for alternative options, such as carbon sequestration (apart from carbon sequestered by bioenergy plants, if such is the case) and biodiversity conservation. Afforesting available productive land may result in considerable carbon sequestration over long (decadal to centennial) periods. Even if no GHG costs of land conversion for bioenergy are factored in, it is not a priori clear whether use of the land for bioenergy production or for carbon sequestration is the superior option in terms of total GHG mitigation, at least over decadal time frames. Indeed, in many cases, carbon sequestration may be more beneficial for the climate than bioenergy (Smith et al. 2013). In many instances, carbon sequestration helps build up biologically more diverse biotic communities (Essl and Rabitsch 2013), so there are probably synergies between carbon sequestration and biodiversity protection.

14.4 Conclusions

Land is a unique resource for humans and for all other living beings on earth. Managing this limited resource in a manner that provides critical resources for humans while minimizing adverse effects for biodiversity or degrading critical ecosystem functions and services is a complex endeavor. On a planet where most of the terrestrial ecosystems are colonized to an extent that patterns and processes must be understood as coupled socioecological systems, changes in land-use practices and resource use create systemic feedbacks affecting ecosystems and the services they provide to human societies. Land-use changes are thus likely to affect the interests of many stakeholders, thereby raising issues of land-use competition or even conflicts.

Systemic feedbacks between demand and supply, among different land characteristics (e.g., biological diversity, landscape values, carbon sequestration and suitability for infrastructure, food provision or as living space for humans) and between different technologies and practices abound, and they carry the potential for enormous unforeseen or unintended consequences. The doubling or tripling of the price of many agricultural commodities in 2007, which most likely resulted from the coincidence of biofuel policies in the US and Europe with changes in demand for food products and a poor harvest (Coelho et al. 2012), is a good example of the possible magnitude of such systemic feedbacks. Another example is the GHG emissions that may result (indirectly through market-mediated effects) from the expansion of bioenergy production, the so-called 'indirect land-use change', or iLUC, effects. At present, these effects are poorly understood, but it has become clear that they are large enough to cast doubt on the potential positive outcomes of policies requiring a large fraction of the land surface of the planet—at least as long as these feedbacks have not been thoroughly studied.

What the sociometabolic approach shows is that demand reductions have positive synergistic effects. They reduce area demand and hence allow a reduction in the intensity of the colonization of ecosystems by reducing the need to boost yields and intensify grazing, or they allow land to be spared for uses other than food production, be it bioenergy, carbon sequestration and/or the conservation of biodiversity. The mixture of these options that is most beneficial is a difficult question for which there are no sweeping answers. Most likely, locally and regionally adapted solutions will help to increase benefits and reduce risks. As shown above, demand reductions can come from changes in diets. These could, in many parts of the world, also be beneficial in terms of health co-benefits. Another option is to reduce food waste, which has been estimated to exceed one-quarter of all food produced globally (Smith et al. 2013).

A largely complementary option suggested by the sociometabolic approach is to increase the efficiency with which biomass is used to generate a variety of products, including feed, food, fiber and energy. This strategy has been denoted the 'cascade utilization of biomass' (Haberl and Geissler 2000). It relies on using by-product and residue flows as well as reuse and recycling of biomass-based products whenever possible. Such optimization may help to generate more products and services from the same amount of primary biomass harvested. However, biomass residue backflows to the soil need to be considered when planning such measures. Otherwise, adverse effects on soil fertility as well as on the soil's carbon balance may ensue (Blanco-Canqui and Lal 2009).

Finally, it is important to question the ceteris paribus conditions invoked in many scenario analyses, namely, the assumption that everything else would stay the same if one factor, such as yields or feeding efficiencies, changed. This assumption, which is often a methodological necessity in mechanistic models, is quite unlikely to prevail in reality. BioBaM partly overcomes this limitation by systematically combining variants of many decisive land-use factors, thereby allowing a multitude of possible future options to be explored. This strategic orientation comes at a cost, however: it is impossible to judge which of the scenarios

is more or less probable than others given certain socioecological developments or policy interventions. Furthermore, BioBaM cannot depict meta-level feedbacks in the land systems, such as rebound effects between technological progress and consumption levels. Moreover, some assumptions, such as the 'food first' and 'no deforestation' approaches, are unlikely to be an accurate description of future trajectories. It seems rather likely that such effects may occur. Food-fuel competition is likely to happen and deforestation may continue, even if it has slowed in some countries in recent years. In our view, increases in efficiency likely played a role in regions that adopted more wasteful lifestyles and diets. Policies based on fostering yield growth and efficiency may thus be ineffective in terms of reducing environmental pressures if not combined with efforts on the demand side in the same way that policies focused on organic agriculture may be ineffective if they do not succeed in changing demand patterns along with production and supply. Coping with trade-offs and maximizing synergies whenever possible is a central challenge in managing the earth's lands sustainably and to the benefit of humans and all other species on earth.

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Method Précis: Human Appropriation of Net Primary Production (HANPP)

Helmut Haberl

The human appropriation of net primary production(HANPP) is an indicator of the intensity of the colonization of ecosystems, namely, the intensity of land use. HANPP is based on the quantification of human interventions in energy flows in ecosystems or, more precisely, in net primary production and the availability of the products of net primary production (primarily biomass) in ecosystems.

Net primary production (NPP) is a measure of the quantity of organic material produced by plants through photosynthesis from inorganic materials. In energetic terms, photosynthesis involves the transformation of radiant energy from the sun into energy stored in chemical compounds. This energy is initially stored in the biomass of plants and then either accumulates in the ecosystem or serves as food energy for humans, animals, fungi and some microorganisms (so-called 'heterotrophic' organisms). During photosynthesis, CO_2 is absorbed from the atmosphere and stored in a variety of chemical compounds in biomass. If this energy is released, for example, through combustion or the metabolism of heterotrophic organisms ('respiration'), then carbon is released into the atmosphere in the form of CO_2. In the short term, ecosystems may represent a 'carbon sink' (that is, absorb more CO_2 through photosynthesis than flows back to the atmosphere due to respiration and combustion) or a 'carbon source' (CO_2 outflows exceed photosynthesis). In the long term and across larger areas, the average absorption and release of CO_2 from ecosystems is largely balanced;[6] that is, CO_2 inflows equal CO_2 outflows (Körner 2009). NPP is an important process in ecosystems; it supplies the entire food energy for humans and all other heterotrophic food webs and provides the basis for the creation of vegetation cover and soils and their associated carbon stocks. NPP is one of the most important indicators of ecosystem capacity and forms the basis for the existence of all biodiversity (Vitousek et al. 1986; Wright 1990).

Insofar as humans use land for their purposes, they intervene in these processes. First, they replace natural ecosystems, such as forests and grasslands, with ecosystems utilized by humans, such as settlement areas, agricultural ecosystems and managed forests (possibly causing soil degradation in the process). The NPP of the ecosystems thus utilized often differs significantly from that of natural ecosystems. The difference between the NPP of potential natural vegetation (NPP_{pot}, NPP of the ecosystem with no human influence) and the vegetation that is predominant due to the land use at a particular point in time (NPP_{act}, *actual* NPP) is defined as $HANPP_{luc}$ (HANPP resulting from land use). Added to this—and this is, in many instances, the actual purpose of land use—is the harvest of biomass for

[6]Exceptions include raised bogs, which are able to create long-term carbon sinks because of the exclusion of oxygen in the soil.

human use ($HANPP_{harv}$, HANPP through harvest). In the current definition, which underpins the research presented in this book (see Haberl et al. 2007, 2014; the notation used here was taken from Krausmann et al. 2013, yet the concept remains the same), $HANPP_{harv}$ is relatively broadly defined and includes those parts of plants that, although they are not themselves economically utilized and actually removed, die off during the harvest. These include, for example, the roots of cereal crops and trees (by contrast, the rootstocks of perennial grasses survive the harvest and are therefore not included in calculations) and the harvest of by-products that remain on the field. In contrast to $HANPP_{harv}$, which is always greater than or equal to zero, $HANPP_{luc}$ can also be less than zero. This is the case when land use increases NPP, which is a common occurrence where artificial irrigation is employed in agriculture. However, land use can also increase NPP in humid regions, for example, in very intensively used agricultural regions. Nonetheless, the NPP_{act} of agricultural ecosystems is often smaller than the NPP_{pot}. The primary purpose of agriculture is to favor the cultivation of plants that produce a greater quantity of plant matter that can be utilized for human food, livestock feed or other economic purposes than natural vegetation would. Examples of usable plant matter are cereal grains and hay rather than unusable leaves or roots. Agriculture is primarily interested in an increase in the economically valuable parts of plants. Whether the NPP of the system rises or falls in the process is not per se important in economic terms but only inasmuch as this produces an increase in the desired harvest. HANPP can therefore be defined as follows (Haberl et al. 2007, 2014):

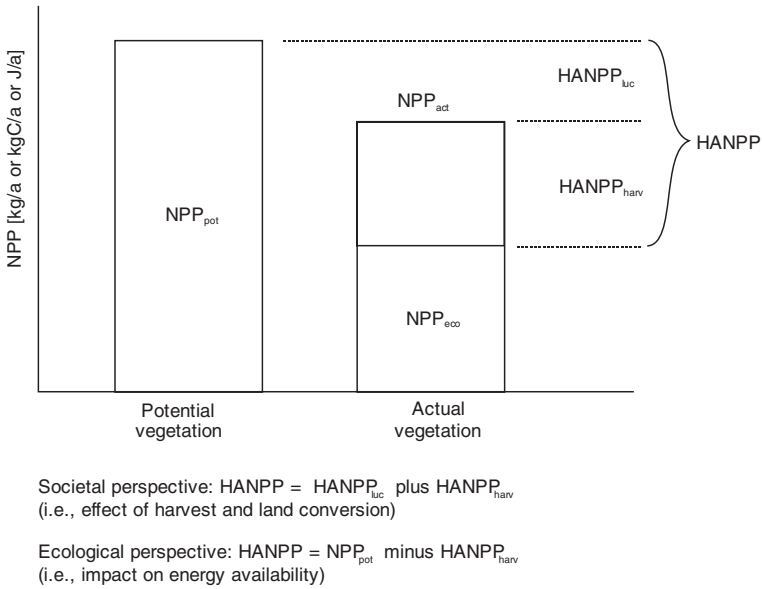

Fig. 14.5 The concept of the human appropriation of net primary production (HANPP)

$$\text{HANPP} := \text{HANPP}_{\text{luc}} + \text{HANPP}_{\text{harv.}} \tag{14.1}$$

If one subtracts the $\text{HANPP}_{\text{harv}}$ from the NPP_{act}, the result is the amount of NPP remaining in the ecosystem after harvest (and thus available to fulfill the ecosystem functions described above, i.e., the food required by heterotrophic organisms or the production/maintenance of carbon stocks). This is defined as NPP_{eco} (NPP remaining in the ecosystem). An equivalent definition of HANPP is, therefore (Fig. 14.5),

$$\text{HANPP} := \text{NPP}_{\text{pot}} - \text{NPP}_{\text{eco.}} \tag{14.2}$$

HANPP can be positive or negative, although a negative HANPP ($\text{NPP}_{\text{eco}} > \text{NPP}_{\text{pot}}$), as a rule, only occurs in arid areas with a low NPP_{pot}, which must be irrigated for agricultural purposes. In other words, HANPP is negative when $\text{HANPP}_{\text{luc}}$ is negative and the absolute value of $\text{HANPP}_{\text{luc}}$ is greater than $\text{HANPP}_{\text{harv}}$. This occurs in arid areas, not in humid regions where intensive agriculture is practiced.

In the literature, other definitions of HANPP are sometimes used, particularly the formulation of Vitousek et al. (1986). The definition used here is a further development of the definition produced by Wright (1990). The influential study by Imhoff et al. (2004) used a consumption-based approach similar to 'embodied HANPP' (Chap. 16). As shown by Haberl et al. (2007), the results of HANPP calculations vary significantly according to the definition used. It is thus of decisive importance that the particular definition used be taken into consideration when interpreting HANPP data.

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