# Eating the Planet: Feeding and fuelling the world sustainably, fairly and humanely – a scoping study

Final report

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Compassion in World Farming, River Court, Mill Lane, Godalming, Surrey GU7 1EZ, UK
Friends of the Earth, 26-28 Underwood Street, London N1 7JQ, UK

Karl-Heinz Erb,[1] Helmut Haberl,[1] Fridolin Krausmann,[1] Christian Lauk,[1] Christoph Plutzar,[1]
Julia K. Steinberger,[1] Christoph Müller,[2] Alberte Bondeau,[2] Katharina Waha,[2]
Gudrun Pollack[1]

[1] Institute of Social Ecology, Alpen-Adria Universität Klagenfurt – Graz – Wien, Schottenfeldgasse 29, 1070 Vienna, Austria, http://www.uni-klu.ac.at/socec
[2] Potsdam Institute for Climate Impact Research, PIK Potsdam, Telegraphenberg A 31, D-14473 Potsdam, Germany, http://www.pik-potsdam.de

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# Table of Contents

# Tables

# Figures

# Abstract

The surging demands of a growing and increasingly affluent world population are confronting the natural world with mounting pressures. Human use of the earth's land for agriculture, forestry or infrastructure is degrading the ability of many ecosystems to deliver vital services to humanity. While modern agricultural technologies have resulted in rapid increases in yields and efficiencies, they have also caused significant and widespread negative environmental effects. Here, we aim to contribute to one of humanity's grand challenges: assessing how we can feed and fuel the world sustainably, fairly and humanely in the future.

Based on several large and consistent databases for the year 2000, we develop a biomass-balance model that calculates the balance between global biomass demand (food and fibre) and global biomass supply from cropland and grazing land for 11 world regions, 11 food categories, seven food crop types and two livestock categories as well as a global bioenergy potential from cropland and grazing areas. Forestry is beyond the scope of this study. We evaluate the possible effect of climate change on yields using a coupled plant growth and water balance model (LPJmL) to calculate the effect of climate change on cropland yields, thereby modelling both the inclusion and exclusion of the poorly understood $CO_2$ fertilization effect.

We develop a consistent set of assumptions to analyze the situation in the year 2050. We use the United Nations medium population forecast (9.16 billion in 2050) to project global demand for infrastructure areas and to calculate total food demand. We use FAO projections of world agriculture in 2050 as a crop intensification scenario, where crop yields are forecast to grow by 54% on average and cropland area grows by 9%. This is compared with two other crop production scenarios: 'wholly organic' crop production and an 'intermediate' crop yield scenario, reflecting a mix of farming systems that create a mean yield between the 'FAO intensive' and 'organic' crop systems. We assess four different diets, ranging from a 'western high meat' diet – high calorie (3 171 kcal/cap/day), rich in animal protein (44% of protein intake) – to a nutritionally sufficient 'fair less meat' diet with 2 800 kcal/cap/d, sufficient protein and fat and low in animal protein. We assume three different livestock rearing systems ('intensive', 'humane' (free range), and 'organic'). We assess two estimates of land use for cropland expansion (+9%, +19%). This results in 72 scenarios, each of which is classified as 'feasible' if calculated cropland demand is 95% or less of the cropland available in 2050, 'probably feasible' if cropland demand differs from available cropland by less than 5% and 'unfeasible' if cropland demand exceeds available cropland by 5% or more.

Results suggest that feeding the world with organic crops and an organic livestock system is probably feasible. This would require a growth in global cropland area by approximately 20% and the adoption of a diet with on average 2 800 kcal/cap/day and 20% of protein from animal sources. While this diet is nutritionally sufficient, a high degree of equality in food distribution would be required to avoid malnutrition. The 'western high meat' diet outlined above is also probably feasible but providing so much food would require a cropland expansion of 20%, 'FAO intensive' yields and 'intensive' livestock production. The diet in 2050 that would result from a continuation of current trends is found to be 'probably feasible' in combination with +9% cropland expansion, 'intermediate' yields and 'organic' as well as 'humane' livestock rearing systems.

We find that the potential for producing primary (mostly solid) biomass for bioenergy production in 2050 ranges from 58 to 161 EJ/yr. The bioenergy potential depends strongly on the choice of diet: it is lowest in the case of the richest diet and highest in the case of the 'fair less meat' diet. Climate change could have a positive or a negative impact on the global food and bioenergy system: In the absence of a $CO_2$ fertilization effect, climate change could have a significant negative impact on food and bioenergy provision, whereas the effect could also be strongly positive if the $CO_2$ fertilization effect is fully taken into account.

# Executive summary

## Introduction

The surging demands of a growing and increasingly affluent world population are confronting the natural world with mounting pressures. Increased land use is already degrading the ability of many ecosystems to deliver vital services to humanity (Millennium Ecosystem Assessment, 2005). While modern agricultural technologies have resulted in rapid increases in yields and efficiencies, they have also caused significant and widespread negative environmental effects (IAASTD, 2009). As a result, the degradation of soil and ecosystems progresses around the world. Biodiversity is lost at a pace that exceeds natural rates of species loss by several orders of magnitude. Agriculture is both affected by, and can exacerbate, climate change. Providing sufficient food and fuel for the world sustainably, fairly and humanely in the coming decades is therefore one of the grand challenges humanity currently faces.

This study analyzes several important objectives for global food and fuel production and use, as well as interrelations and possible trade-offs between these:

- Feeding the world fairly: that is, aiming to reduce or even eradicate the contrast between overconsumption and malnourishment or even hunger in different world regions.
- Reducing the environmental pressures resulting from agriculture by adopting organic or at least environmentally less demanding technologies.
- Reducing the amount of animal suffering through adoption of humane methods of livestock rearing.
- Providing plant biomass for energy provision as a substitute for fossil fuels if it can be sustainably produced and effectively reduces greenhouse gas (GHG) emissions.
- Protecting areas of high biodiversity value such as pristine tropical forests.

An analysis of these objectives needs to take the following global trajectories into account:

- The growth in global population numbers is likely to increase the global socioeconomic use of biomass for food and fibre.
- Growing affluence, and attempts at eradicating world hunger and improving human diets in poor countries, will push up biomass demand.
- Climate change may have substantial and as yet highly uncertain consequences for agriculture and forestry.

None of the global integrated assessment models incorporates sufficient detail on farming practices or biomass utilization pathways as would be needed to answer these questions and to analyze all the feedbacks that have to be understood in that context. This report provides a scoping study of the magnitude of the challenges, based on a data-driven approach. Using a highly detailed database for the year 2000, we derive scenarios for the situation around 2050, based on a set of assumptions on population growth, diets, agricultural technology, etc., as explained below.

We use the UN medium population forecast (UN, 2007) and agricultural forecasts by the FAO (Bruinsma, 2003, FAO, 2006), which we interpret as a 'business-as-usual' scenario that describes a strong crop production intensification trajectory and is very optimistic in terms of future yields. We construct a biomass-balance model that allows us to build consistent scenarios of supply and demand of biomass based on a consistent set of data for 2050 on cropland

and grazing area, biomass yields on cropland and grazing land, feed conversion efficiencies of livestock, depending on livestock rearing system, and conversion losses in the biomass flow chain from production to final consumption. The biomass-balance model is used to assess the feasibility of combinations of diet, yields, feeding efficiencies and cropland expansions and to calculate the bioenergy potential in each scenario.

Because this is a scoping study, in some cases, data were lacking to build the calculations on more than educated estimates. Therefore, the study results should be taken as fuel for thought and discussion. They demonstrate what the world might look like if our assumptions were correct. The authors will be grateful for any suggestions on how to further improve this work.

## Methods and data

*Study regions and biomass categories*

The regional grouping we use is based on the classification of the continental regions and geographical sub-regions as defined by the United Nations Statistical Division (UNSD 2006, see Figure S1). These regions vary considerably with respect to per-capita income/GDP, population density, agricultural systems, soils, climate and many other important factors.

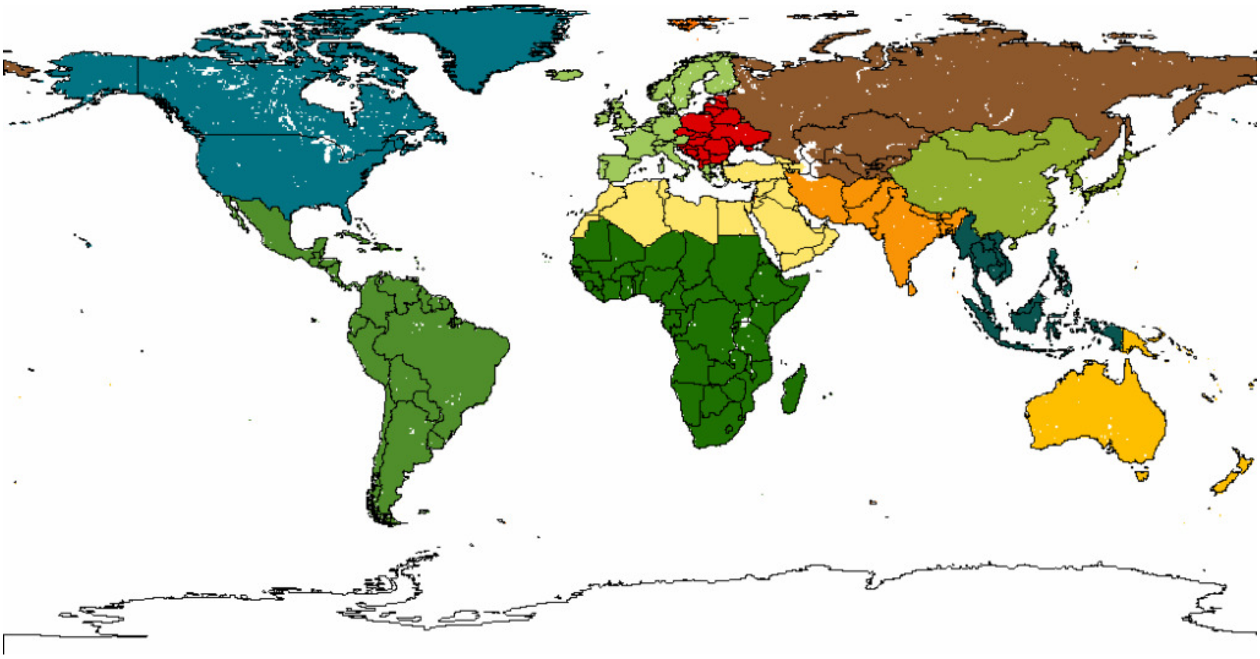


**Figure S1. World regions used in this study.**

Population density is low in the Americas, in Oceania, Africa, and in Central Asia and the Russian Federation. Population density is high in South, South-East and East Asia and in Europe. Incomes are high in North America, Europe and Oceania, intermediate in East Asia, Latin America, and North Africa and Western Asia, and low everywhere else. Agricultural intensity is highest in East Asia and Western Europe, very low in Sub-Saharan Africa and somewhere between these extremes everywhere else.

We use the following categories when working with biomass production and consumption flows (for reference, see Erb et al., 2009). We distinguish 11 food categories (cereals; roots and tubers; sugar crops; pulses; oil crops; vegetables and fruits; meat of ruminants (grazers); milk, butter and other dairy products; meat of pigs, poultry and eggs; fish; other crops). We use seven food crop aggregates (cereals; oil-bearing crops; sugar crops; pulses; roots and tubers; vegetables and fruits; others). We distinguish two groups of livestock: all animals capable of digesting roughage are grouped into the 'grazers' group (cattle, sheep, goats, etc.). All other animals (above all pigs and poultry) are grouped into 'non-grazers'. All data are converted into dry matter.

### *Data on land use and global biomass flows in the year 2000*

Our analysis is based on a global database for the year 2000 that integrates global land-use and socioeconomic data with data on plant growth (net primary production, abbreviated NPP; that is, the amount of biomass produced by green plants through photosynthesis) across a range of spatial scales, from grids to the country level (~160 countries; see http://www.uni-klu.ac.at/socec/inhalt/1088.htm). The database covers three domains of data that were cross-checked against one another and are consistent between scales (grid and country level) and domains (NPP, biomass harvest, byflows, livestock, biomass processing and use). The three main datasets used are:

- A geographically explicit (10x10 km at the equator) land-use dataset (Erb et al., 2007), see Table S1. Cropland area and forest area are consistent with FAO data on cropland and the large forest resource assessments (the 'Forest Resource Assessment' [FRA] and the 'Temperate and Boreal Forest Resource Assessment' [TBFRA] of the FAO) on the country level. Grazing land is classified according to its suitability for grazing, discerning 4 classes (class 1 denoting the best suited, class 4 the least suited grazing areas).
- A geographically explicit (10x10 km at the equator) assessment of the global human appropriation of net primary production (abbreviated HANPP; Haberl et al., 2007). HANPP is an indicator of land-use intensity that is defined as the difference between the net primary production (NPP) of potential vegetation and the amount of NPP remaining in ecosystems after harvest. The database includes, for each grid cell, $NPP_0$ (NPP of potential vegetation), $NPP_{act}$ (NPP of the currently prevailing vegetation), and $NPP_h$ (biomass harvested by humans, grazed by their livestock or destroyed during harvest or by human-induced fires).
- A country-level assessment of socioeconomic biomass use that traces biomass flows from harvest to final consumption (Krausmann et al., 2008). Flows not covered in statistics were estimated (e.g., grazing of livestock) based on country-level feed balances of all major livestock species. Biomass harvest was calculated from the FAO agricultural production database (FAO 2004).

The land-use data in Table S1 show that 75.5% of the earth's land (excluding Greenland and Antarctica) is already used by humans. Land use ranges from very intensive to very extensive. 1% of the land is used as infrastructure and urban area, 11.7% as cropland, 26.8% as forestry land, 36.0% as grazing land. Grazing land is characterized by four quality classes (1-4, with 1 denoting the best grazing land and 4 the worst). Grazing land includes a large variety of ecosystem types, from intensively cultivated meadows to barely productive semi-natural landscapes that often have a very high ecological value. Of the remaining 24.5%, about one half is completely unproductive, often covered by rocks and snow or deserts with very low NPP ('non-productive land' in Table S1). The other half ('unused productive land') includes pristine forests (6 mio. $km^2$, 4.6% of total area), including tropical rainforests as well as all other forests with almost no signs of human use (most of the latter in boreal regions). This category also includes rather unproductive ecosystems such as arctic or alpine tundras and grasslands. Table S1 reveals that most of the earth's land is already used by humans, and that the land that is not yet used has either very low productivity or should not be used due to its high conservation value (pristine forests).

**Table S1. Land use in the 11 study regions in the year 2000**

| | Infra-structure | Cropland | Forestry | Grazing land [1 000 km$^2$] | Non-productive land | Unused productive land | Total |
|---|---|---|---|---|---|---|---|
| N. Africa and W. Asia | 42 | 763 | 268 | 1 738 | 7 421 | 47 | 10 279 |
| Sub-Saharan Africa | 111 | 1 781 | 5 828 | 11 867 | 3 443 | 945 | 23 975 |
| Central Asia and Russian Fed. | 189 | 1 572 | 7 155 | 6 742 | 280 | 4 494 | 20 432 |
| E. Asia | 140 | 1 604 | 2 121 | 5 146 | 2 075 | 448 | 11 533 |
| S. Asia | 113 | 2 305 | 850 | 2 554 | 824 | 024 | 6 670 |
| S.-E. Asia | 039 | 931 | 2 098 | 1 331 | 0 | 83 | 4 483 |
| N. America | 337 | 2 240 | 4 741 | 4 473 | 1 549 | 5 169 | 18 508 |
| Latin America & the Carribean | 64 | 1 685 | 8 733 | 7 932 | 256 | 1 624 | 20 295 |
| W. Europe | 198 | 862 | 1 318 | 1 130 | 11 | 136 | 3 655 |
| E. & S.-E. Europe | 103 | 941 | 630 | 482 | 0 | 2 | 2 158 |
| Oceania and Australia | 23 | 540 | 1 216 | 3 484 | 305 | 2 817 | 8 385 |
| World | 1 360 | 15 225 | 34 958 | 46 881 | 16 163 | 15 788 | 130 375 |

### *Matching supply and demand: the biomass balance model*

The biomass balance model (for reference, see Erb et al., 2009) allows a calculation of scenarios for the supply and demand of biomass in 2050, based on assumptions discussed in the next section. The databases described above are used to build a model of biomass flows in the year 2000 in which the demand for final products is matched with gross agricultural production and land-use data (Figure S2). Factors derived from data for 2000 are used to characterize the conversion of biomass in agriculture, food and other industries as well as livestock input-output ratios. The model consists of two calculations: a food crop calculation for the demand for cereals, roots and tubers, sugar crops, pulses, oil crops, etc., and also for the demand for pig meat, poultry and eggs, and a roughage calculation for the demand for products derived from grazers (meat, milk, butter, etc.).

In the food crop calculation, the regional demand for final biomass products (e.g. flour, vegetable oils, refined sugar) is converted to the amount of gross primary crop demand (e.g., cereals, oil crops, or sugar crops). Using global factors derived from the databases described above, the by-products accruing from the production of final products (e.g. brans in flour production from cereals, oil-cakes in vegetable oil production from oilbearing crops), seed requirements and the losses in the agricultural system are calculated (Figure S2).

Non-grazers (pigs, poultry) are dealt with in the food crop calculation as well, because they are fed (mainly) from primary or secondary cropland products. From the demand for final products (e.g., meat from pigs and poultry, eggs), and data on market feed requirement (i.e. feed usually traded on markets; e.g., cereals; non-market feed is usually not traded; e.g., roughage, maize for silage, etc.), regional input-output ratios of the non-grazer livestock systems are calculated. The amount of market feed demand of non-grazers is added to the market feed demand of grazers calculated in the roughage calculation (see below), resulting in total regional market feed demand. This is then balanced against the regional supply of market feed from food processing and industrial processing of cereals, oil-bearing crops, and sugar crops; i.e., the supply of brans, oil-cakes, molasses and bagasse (a by-product of sugarcane). Usage-factors for these categories are derived from the 2000 database and used to calculate the amount of market feed fed to animals. From the difference between market feed demand and the amount of by-products from processing fed to animals, the additional demand for feed grain (cereals) is calculated and added to the regional demand for cereals, taking seed demand and losses into account.

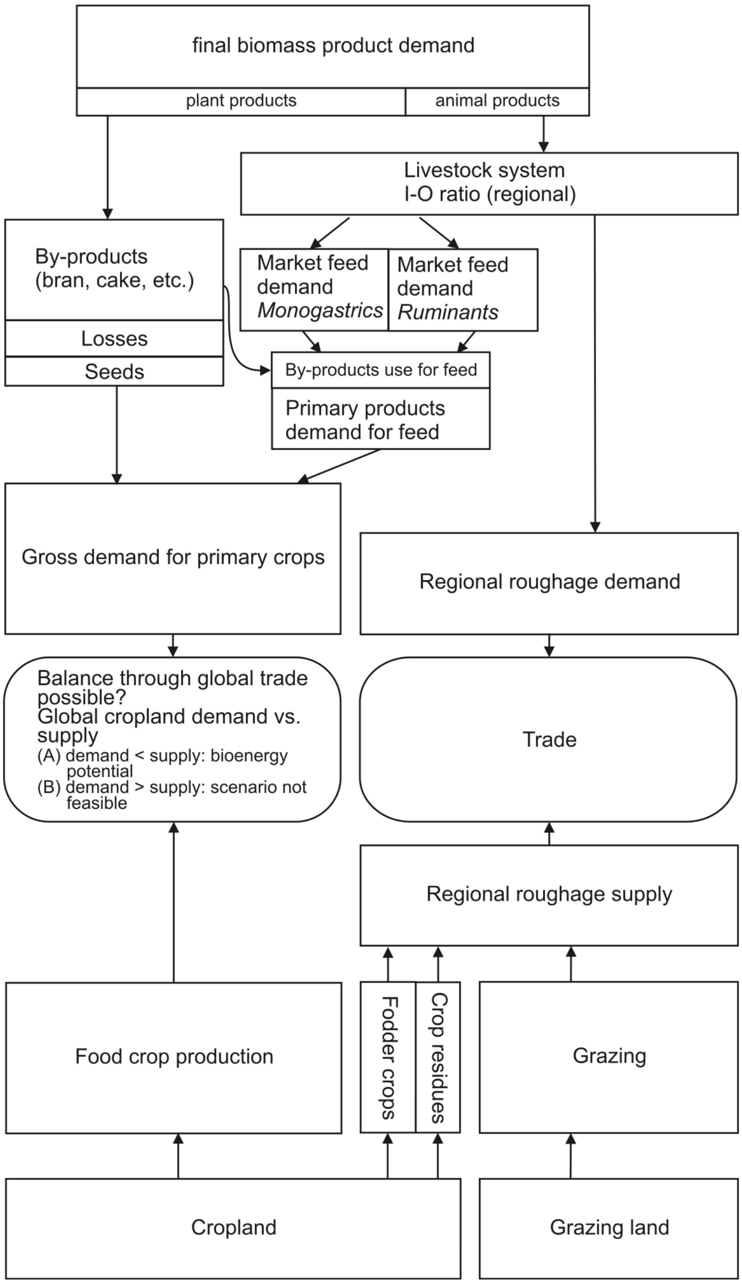


**Figure S2. Overview of the biomass-balance model used in this study.**

The roughage calculation refers to the demand for ruminant meat and milk, i.e. to a grazing livestock system. The grazing livestock system is characterized by a demand for market feed (e.g., brans, oil cakes, cereals) and a demand for non-market feed (roughage demand; i.e., the sum of fodder, crop residues fed to grazers, and grazing). The amount of feed demand per unit of output (meat or milk), derived from the year 2000 database, varies between world regions by factors of up to ten, due to the differences in breed and animal husbandry systems. These factors depend particularly on the regional share of subsistence livestock systems (with high input-output ratios for roughage and low input-output ratios for market feed) and industrial intensive meat and milk production (with the opposite patterns and a much higher overall efficiency due to the higher nutritional value of market feed and a production system optimized for high outputs). For the scenario analysis 2050, these input-output ratios were modulated in order to reflect technological change in this sector.

Due to the large differences in input-output ratios of the regional grazing systems, it is not possible to apply global factors for calculating roughage demand from meat and milk consumption. Instead, we applied the input-output ratios of the regional grazing systems to calculate regional production of meat and milk from data on the amount of crop residues and fodder crops, combined with our estimate on biomass production of grazing lands in 2050 (see below) and assumptions on grazing intensity (i.e. the ratio of the amount of grazed biomass to total biomass production on grazing land). The gap between regional production and demand, for meat as well as for cropland products, is 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.

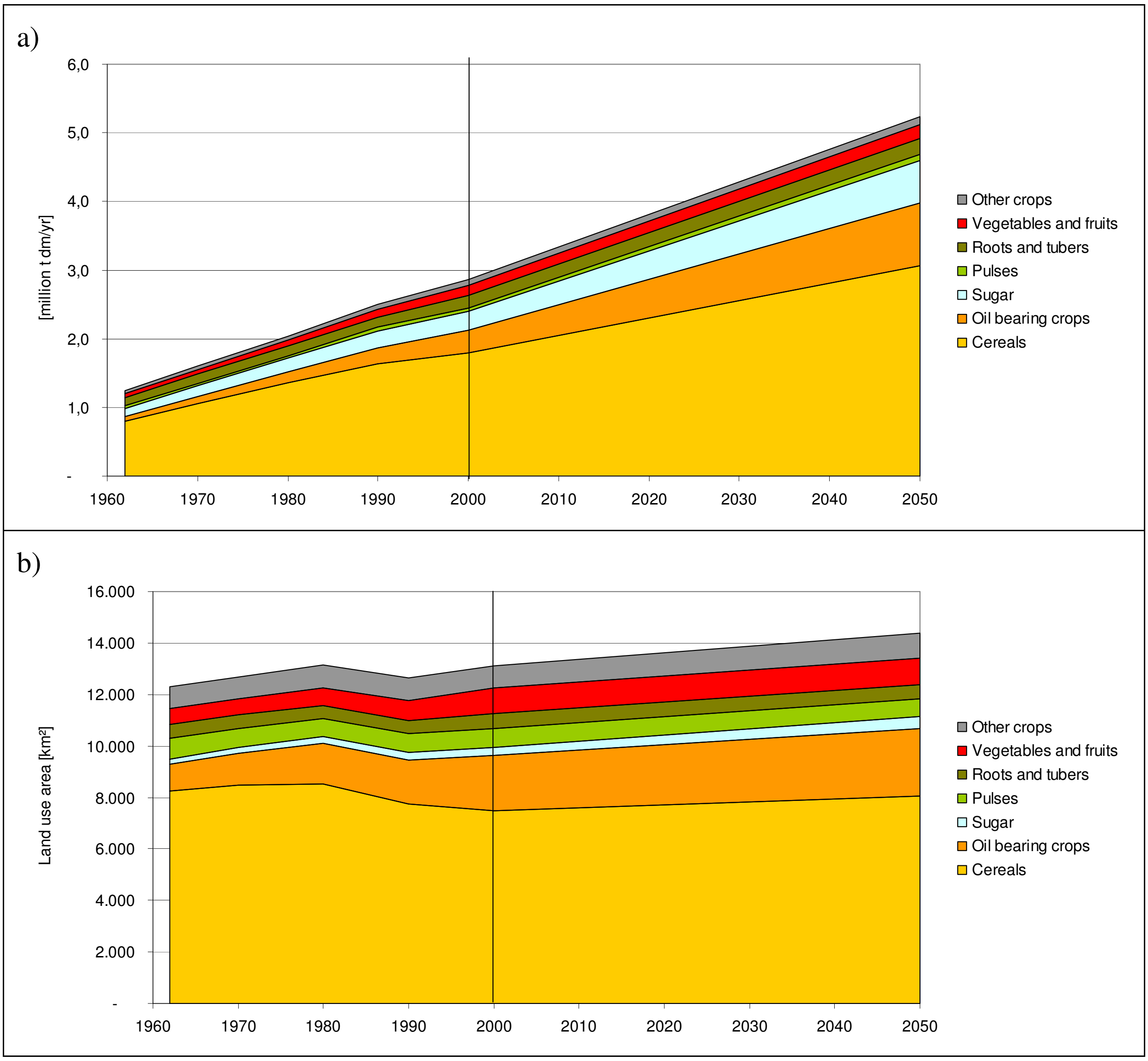
Overall, the level of uncertainty in the biomass flow model is satisfactory: modelled global demand for primary crops is at 98% of the actual 2000 cropland production, and modelled grazing is at 99% of the grazing amount given by Haberl et al. (2007). Discrepancies result from the usage of global average factors. In order to use the model to calculate bioenergy potentials for the year 2050 and to assess the feasibility of diet changes and technologies in 2050, we modify the original model for the year 2000 as described below.

### *Changes in land use and agriculture until 2050 according to the FAO*

We explicitly take urban and infrastructure areas into account. In order to do so, we derive a forecast of these areas as follows. We start with population growth, based on the UN medium variant in which world population is forecast to be 9.16 billion in 2050 (UN, 2007). Urban areas are much smaller than rural infrastructure. Urban areas in 2050 are estimated by assuming that the per-capita amount of urban area would stay constant from 2000 to 2050. Globally, urban population is forecast to increase from 2.84 to 6.37 billion (UN, 2008). For East and South-East Europe, the UN forecasts a shrinking urban population; in this region we keep the urban areas constant. We are aware that such simple assumptions can only serve to derive first-order approximations that might be too low, therefore the results may be conservative. According to our calculation, urban areas grow from 279 180 km$^2$ to 532 880 km$^2$. This is not much when compared with existing cropland areas (Table S1), so possible errors introduced by our estimation method are small, too. Assuming that rural infrastructure areas are mostly driven by the need to transport agricultural inputs and produce and by the need to house agricultural population and machinery, the area of rural infrastructure is calculated as a percentage of cropland area in each region, using factors derived by Erb et al. (2007).

FAO forecasts (Bruinsma, 2003, FAO, 2006) are used to derive estimates for cropland area change and crop yields until 2050. Our ‘business-as-usual’ assumption on cropland expansion (+9%) is taken from these sources. Assumptions on cropland yields in the ‘FAO intensive’ scenario (for details, see Erb et al, 2009) are also taken from there. The FAO provides projections of crop production for selected important food crops (cereals, oil crops, sugar crops) for industrialised countries and five regional groups of developing countries. Annual growth rates are applied to the data as reported by the FAO to derive total production volumes and area changes for crops and regions explicitly covered by the FAO (Figure S3).

**Figure S3. Cropland production 1961-2050 in the 'FAO intensive' scenario. Development of (a) production and (b) arable land area 1960 – 2050 of food crops.**



The FAO does not report projections for fodder crops. To fill this gap, it is assumed that the share of fodder crops to the overall area of arable land remains constant and that the yields of fodder crops grow with the same rate as the aggregate 'other crops' (with small exceptions; see Erb et al., 2009). The assumptions deviate from the FAO forecast only marginally, especially when compared to the level of uncertainty in such a projection. Overall, in the 'FAO intensive' crop yield scenario, it is assumed that cropland area will grow by 9% and yields by 54%. These assumptions are in line with recent work by the International Institute of Applied Systems Analysis (IIASA) suggesting that the growth of global cropland area will be between +6% and +12% until 2050 (http://www.iiasa.ac.at/Research/GGI/). Most global agricultural scenarios assume that growth in agricultural production will depend mostly on increases of yields and only to a smaller extent on a growth of cropland areas (e.g., IAASTD, 2009).

As this study focuses on agriculture and excludes forestry, the conservative assumption is made that growth in cropland and urban/infrastructure area reduces the area of grazing lands only, while forest areas remain constant. This assumption does not affect the evaluation of the feasibility analysis because grazing areas are not found to be limiting because the biomass production on grazing areas is under all assumptions sufficient to provide the required amount of roughage. It is assumed that the area expansion of cropland and infrastructure consumes the best grazing areas, i.e. that of class 1 and in regions where sufficient grazing land of that quality class is available, and class 2 where this is not the case (i.e. North Africa and Western Asia). The biomass-balance model calculates grazing intensity on grazing land (i.e. the ratio of biomass grazed to biomass production ($NPP_{act}$) on grazing land) as discussed above. The pattern of cropland expansion (Table S2) seems reasonable when compared with studies on global cropland potentials (IIASA and FAO, 2000) and cropland suitability maps (Ramankutty et al., 2002).

### *The 'massive cropland expansion' scenario*

Global studies of land suitable or potentially available for cropland (IIASA and FAO, 2000, Ramankutty et al., 2002) suggest that cropland potentials are considerably larger than those assumed in the 'FAO intensive' scenario discussed above. This study therefore also explores a 'massive cropland expansion' scenario in which it is assumed that cropland expansion doubles in each region for which the FAO forecasts an expansion of cropland and is kept constant elsewhere (Table S2).

**Table S2. Cropland areas and changes in 2000 and 2050, according to estimates based on the FAO 'business as usual' land use ('bau') scenario and the 'massive cropland expansion' scenario.**

| | Cropland in year 2000 | Cropland in year 2050 FAO / BAU | | Cropland in year 2050 massive change | |
|---|---|---|---|---|---|
| | [1000 km²] | [1000 km²] | [change] | [1000 km²] | [change] |
| Northern Africa and Western Asia | 763 | 819 | +7.2% | 874 | +14.5% |
| Sub-Saharan Africa | 1 781 | 2 283 | +28.2% | 2 785 | +56.3% |
| Central Asia and Russian Federation | 1 572 | 1 635 | +4.0% | 1 699 | +8.1% |
| Eastern Asia | 1 604 | 1 694 | +5.7% | 1 785 | +11.3% |
| Southern Asia | 2 305 | 2 428 | +5.3% | 2 550 | +10.6% |
| South-Eastern Asia | 931 | 930 | -0.1% | 931 | 0.0% |
| Northern America | 2 240 | 2 335 | +4.3% | 2 430 | +8.5% |
| Latin America & the Carribean | 1 685 | 2 037 | +20.9% | 2 388 | +41.7% |
| Western Europe | 862 | 880 | +2.1% | 899 | +4.2% |
| Eastern & South-Eastern Europe | 941 | 890 | -5.4% | 941 | 0.0% |
| Oceania and Australia | 540 | 696 | +28.8% | 851 | +57.7% |
| World | 15 225 | 16 627 | +9.2% | 18 134 | +19.1% |

This cropland expansion scenario is still lower than the cropland expansion assumed to occur in some other global scenario studies (IAASTD, 2009). The largest expansion of cropland areas is assumed to occur in Sub-Saharan Africa and Latin America, as these are the regions generally assumed to have the largest cropland potentials (IIASA and FAO, 2000, Ramankutty et al., 2002). How well-suited this land is for large-scale, intensive cultivation is highly contested and uncertain, however. Assessments of cropland potentials are based on scarce data that are extrapolated for large areas. Much of the cultivable land in Sub-Saharan Africa and South America is under valuable forests or in protected areas. Tropical soils could potentially lose fertility rapidly if taken into cultivation and are highly vulnerable to climate-change impacts (Ramankutty et al., 2002). It is estimated that only 7% of the cultivable areas in Sub-Saharan Africa and only 12% of those in Latin America and the Caribbean are free from severe soil constraints that limit sustainable and profitable production (IAASTD, 2009).

*Crop yields in the 'wholly organic' and 'intermediate' scenarios*

The 'FAO intensive' crop yield scenario assumes large increases in yields, i.e. 54% on average for all cropland. In particular, in Western Europe and North America, cropland yields have already reached very high levels. It is difficult to judge to what extent these yield gains can be realized and what the environmental costs of trying to achieve these yields might be (e.g., soil erosion, nitrogen leaching, water pollution or GHG emissions). It has been argued that many options to achieve yield gains have already been discovered and are approaching physiological limits, that the best agricultural lands are already in use and area expansions may result in the use of less well-suited land, and that soil erosion and depletion of nutrient stocks in soils may pose challenges for future yield growth (Cassmann, 1999). On the other hand, improved management could help to sustain yield growth, for example due to improved stress tolerance, avoidance of nutrient and water shortages, or improvements in pest control, in particular in those regions where yields are still lower than they could be due to lack of required inputs. Substantial investments would be indispensable for maintaining such growth in crop yields.

In order to evaluate options for alternative pathways of agricultural development, we derive two additional sets of assumptions. We conduct an in-depth review of the literature on crop yields in organic agriculture and used this to derive an estimate of crop yields in 2050 under 'wholly organic' conditions (i.e., 100% cropland area planted according to standards of organic agriculture). We calculate the arithmetic mean between the 'FAO intensive' and the 'wholly organic' scenarios to derive an 'intermediate' estimate of future cropland yields.

From the literature review documented in Erb et al. (2009) we conclude that organic yields per harvest event (i.e. the yield of a wheat field harvested once) are only slightly (approximately 10%) lower than those of industrialised agriculture (see also IAASTD, 2009). However, organic agriculture requires additional area for planting of leguminous crops and other intercrops that are required to maintain soil fertility; most of these crops have to be ploughed into the soil and are not, or only to a limited extent, available as feed. We estimate that yields in organic agriculture are about 40% lower than those of industrialised agriculture, if calculated over the whole crop rotation cycle. This comparison is only valid for regions with highly intensive cropland systems. In developing countries, we conclude from our review of the literature that organic agriculture could allow for considerable increases in yields, because the nutrient status of croplands is often very poor and can be improved significantly with organic techniques. Accordingly, we assume that yield increases are possible in the 'wholly organic' scenario in regions where yields are low (Figure S4).

The 'intermediate crop yield' scenario was derived by calculating the arithmetic mean between the 'FAO intensive' and 'wholly organic' scenarios. This provides a numerical estimate that could reflect a diversity of mid-range scenarios, such as a situation in which half of the area is managed with organic techniques and the other half with intensive high-yield systems; a situation where cropland agro-ecosystems are not pushed to their very limits due to environmental considerations; or a trajectory in which FAO yield expectations cannot be met for economic (lack of investment) or biophysical (physiological limits, soil degradation, etc.) reasons.

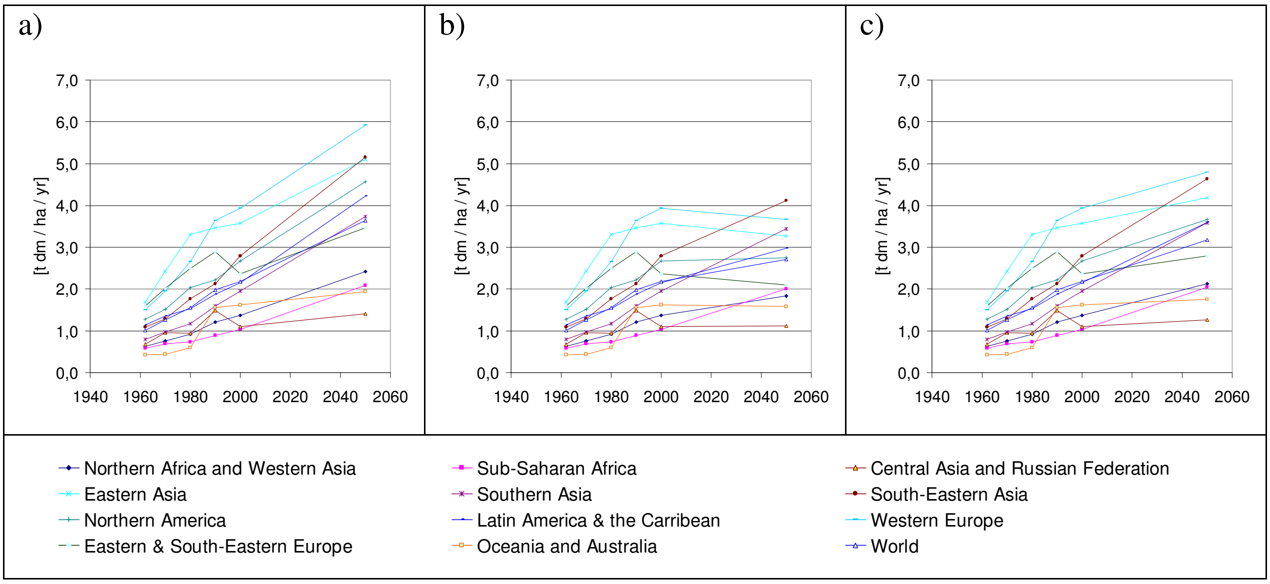


**Figure S4. Agricultural crop yield development 1960 – 2050 under three yield estimates: a) FAO intensive, b) wholly organic yields; c) intermediate.**

### *Livestock feeding efficiencies in intensive, humane and organic agriculture*

Based on statistical data reported by the FAO, we derive trajectories of the input-output ratios of livestock for the time period from 1961 to 2000 at the regional level (Krausmann et al., 2008), which we project until 2050 based on data on feeding efficiencies of different livestock rearing systems. We conducted a literature review on the feeding efficiencies of optimised (intensive/humane/organic) livestock rearing systems (Erb et al., 2009), from which we conclude that producing one ton of dry matter of animal product (meat and eggs in the case of non-grazers, meat and milk in the case of grazers) requires 10% more feed input in the case of humane (free-range) systems and 20% in organic livestock rearing systems (as the latter have stricter standards). We assume that cattle and other grazers do not require additional area for roaming because we assume that they need some minimum amount of grazing land for their roughage supply on which they can also roam. For non-grazers, we calculate the additional land demand for free-range systems according to UK government Department for Environment, Food and Rural Affairs (DEFRA) and similar standards for animal welfare.

In all scenarios, we assume a reduction of the respective regional subsistence fractions by 50% in favour of optimised or extensive, market oriented production systems, depending on area availability. Whereas two thirds of all livestock was kept in subsistence and extensive, market-oriented livestock systems in 2000, we assume that the share of these less intensive livestock systems will drop below 50% in 2050 (subsistence below 20%). The share of the less intensive livestock systems (subsistence and market-oriented extensive) is kept constant in all livestock rearing scenarios. The livestock rearing scenarios differ with respect to three different kinds of systems (intensive, humane and organic) in which feeding efficiency (that is, the ratio between feed input and output of animal products) is optimised. In the 'intensive' animal production scenario, we assume that most optimised livestock rearing systems will adopt intensive, industrial techniques and the share of organic and humane livestock rearing systems will be low. In the 'humane' scenario, we assume that all livestock in optimised systems is kept with access to the outdoor (free-range) according to standards of free-range livestock rearing. In the 'organic' scenario we assume that all livestock in optimised systems is managed according to organic standards, such as those of IFOAM.

*Diet scenarios for 2050 compared to the situation in 2000*

Total food demand is derived from forecast population numbers (UN, 2007), assuming changes in regional diets which we derive as follows. Four diets are defined, based on different calorie counts and varying proportions of animal products. Countries with high gross domestic product (GDP) per capita on average consume more food and have a higher proportion of animal products in the diet than countries with low GDP. For example, the average North American consumes twice as much protein as an average Sub-Saharan African, with almost two-thirds of protein coming from animal products, compared to just one-fifth in the case of an average Sub-Saharan African.

- The **'western high meat'** scenario assumes a fast acceleration of economic growth and consumption patterns in the coming decades, leading to a globalization of western diet patterns and increases in the shares of animal products, sugar and vegetable oil. All the regions attain diets at or above 3 000 kcal/cap/d, an extreme increase for most regions. The protein consumption also increases dramatically, with all regions at or above 80 grams/cap/d.
- The **'current trend'** scenario maintains current growth trends and strong regional differences in the diet levels and compositions. All the regions attain diets above 2 700 kcal/cap/d, and the world average is almost 3 000 (compared to 2 788 in 2000). The per-capita consumption of sugar and oil crops increases by 19% globally, while animal products increase by 7%. All regions attain protein levels of almost 70 grams per capita per day (compared to 60 g in 2000). This scenario represents a quantitative and qualitative improvement in diets for the poorest areas, while the richest areas do not significantly increase or change their diets.
- The **'less meat'** scenario is based on the idea of satisfying growing food demands, both from population growth and better nutritional levels, by a lower meat diet. The diet levels attain the same level as in the 'current trend' scenario, but with 30% of the protein coming from animal products. The total protein levels are nutritionally sufficient, but the average protein consumption of North America and Western Europe decreases, and the distribution of food categories changes. The cereals, roots, pulses, vegetables and fruits categories rise above 1 700 kcal/cap/d for all regions, even for the richer regions where they were lower in 2000, while the animal products, sugar and oil crops shares decrease, in particular in rich regions, and the level of protein consumption decreases compared to the business-as-usual scenario.
- The **'fair less meat'** scenario goes beyond the 'less meat' scenario, reducing the fraction of protein from animal sources to 20%. Moreover, a universal diet level of 2 800 kcal/cap/d is imposed. In order to maintain adequate nutrition, protein consumption is close to 75 g/cap/d, or higher. These values are close to the 2000 global average levels. These constraints leave very little room for diet variation between the world regions. In particular, the richest regions reduce their share of animal products, sugar, and vegetable oil, reductions which are considered beneficial both for human health and the environment.

All four diets are nutritionally adequate, in an average sense, in terms of energy, protein content and diversity of food sources. The 'fair less meat' scenario models a level of food supply at which it would be possible to avoid malnutrition if a fair and equal distribution of food is achieved: at that level of calorie supply, any significant inequality in food supply would cause malnutrition. The two scenarios with lower animal protein are based on environmental concerns: the lower the percentage of animal product consumption, the more environmentally sustainable a diet is, because of the inefficiency of meat production and the environmental pressures associated with livestock. Both the ‘less meat’ and ‘fair less meat’ scenarios are would require significant cultural and attitudinal change and policy intervention. They are included here to understand how substantial the environmental and food security benefits could be from a shift away from animal products.

**Table 3. Diet scenarios for 2050 compared to the situation in the year 2000.**

| | Dietary energy | | Protein | | Share of protein from animal products | Business-as-usual evolution of diet | Globally equitable distribution of food |
|---|---|---|---|---|---|---|---|
| | [kcal/cap/ day] | [fraction of 2000 value] | [g/cap/ day] | [fraction of 2000 value] | | | |
| Status in 2000 | 2 788 | | 75 | | 37% | | |
| Western high meat | 3 171 | (114%) | 92 | (122%) | 44% | X | |
| Current trend | 2 993 | (107%) | 79 | (106%) | 38% | X | |
| Less meat | 2 993 | (107%) | 74 | (98%) | 30% | | |
| Fair less meat | 2 800 | (100%) | 75 | (100%) | 20% | | X |

In terms of the global quantity of animal products consumed, the scenarios differ considerably. Under ’current trend’, the total amount of animal products increases by 62% compared to 2000, and it more than doubles with the ‘western high meat’ scenario. The ‘less meat’ scenario leads to a 20% increase in animal products, despite the lower consumption levels of industrialised countries, because of the increase in consumption levels and population in the poorest areas. In contrast, the ‘fair less meat’ scenario leads to a decrease of 23% in animal products compared to 2000.

Global fish yields are not expected to increase; in fact it is assumed that they will decrease due to overfishing. In all scenarios, we assume that overall fish consumption remains constant, resulting in a decreasing per-capita fish consumption. The lower fish fraction in the diet is compensated by increases among the other food categories.

### *Calculation of bioenergy potentials*

We calculate bioenergy potentials by distinguishing three fundamentally different production pathways: (1) bioenergy crops on cropland, (2) bioenergy crops on grazing land, and (3) residue potentials on cropland. We calculate gross potentials for bioenergy supply by assuming that the entire aboveground NPP of bioenergy crops can be used to produce bioenergy, assuming a gross calorific value of dry-matter biomass of 18.5 MJ/kg. This calculation does not take conversion or production losses into account.

In order to calculate the bioenergy potential on cropland, we subtract the area required in each region for food, feed and fibre (calculated using the biomass-balance model) from each region’s cropland area according to the respective scenario estimate. This gives the area of cropland available for bioenergy crops. We calculate the bioenergy potential by assuming that the productivity of the bioenergy plants equals potential net primary production ($NPP_0$, see above) on cropland and that the entire aboveground biomass can be harvested and used to produce bioenergy. $NPP_0$ data are taken from Haberl et al. (2007).

To calculate the potential to grow bioenergy crops on grazing areas, we assume that grazing land of quality class 1 is also suitable for producing of bioenergy crops such as switchgrass

(*Panicum virgatum*), other perennial grasses such as *Miscanthus sp.*, short-rotation coppice or similar bioenergy crops. We assume that grazing on land in grazing quality class 1 can be intensified, assuming an exploitation rate of 67% of $NPP_{act}$ in developing and 75% in industrialised regions. This allows use of a significant fraction of the area in grazing land of quality class 1 for bioenergy crops without reducing regional roughage supply. On the area that becomes available for bioenergy crops through intensification, the bioenergy potential is estimated to be equal to the current actual productivity ($NPP_{act}$) of these areas (taken from Haberl et al., 2007).

The energy potential from unused residues on cropland is calculated by applying harvest indices and usage factors as used in the biomass-balance model. Crop residues are used as feedstuff and for bedding. The bedding requirement is estimated by calculating the amount of manure produced by livestock and applying factors to estimate bedding demand from manure production in the optimised systems (Krausmann et al., 2008). We assume that 50% of the remaining residues are required to maintain soil fertility and should therefore not be used to produce bioenergy. We are aware that this is a crude assumption and that higher or lower shares of the residues might be required to maintain soil fertility in different regions, depending on soil and climate conditions (WBGU, 2008).

### *Modelling of climate change effects with LPJmL*

We employ the 'LPJmL' model (Bondeau et al., 2007) to estimate the effects of changes in temperature, precipitation and $CO_2$ fertilization on yields of major crops globally at a spatial resolution of 0.5°x0.5°. Yield simulations are based on simulations of 11 agricultural crops in the mechanistic coupled plant growth and water-balance model LPJmL that is able to calculate the dependence of plant growth on climate, soil etc. in a 'process-based' manner; that is, based on plant physiological characteristics of different plant types.

We calculate percent changes in agricultural productivity between two 10-year periods: 1996-2005 and 2046-2055, representing the average productivity of the years 2000 and 2050. Management intensity is calibrated to match national yield levels as reported by FAO statistics for the 1990s (FAO 2004). National and regional agricultural productivities are based on calorie- and area-weighted mean crop productivity of wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed. LPJmL simulations are used only to estimate the possible magnitude of the climate-change effect on agricultural yields. In these simulations we assume constant management intensities and cropping patterns as of the year 2000. We do not consider feedbacks between climate change, $CO_2$ fertilization and management.

We assume three different scenarios of future greenhouse gas emissions as elaborated by the Intergovernmental Panel on Climate Change (IPCC). Emission scenarios were taken from Nakicenovic and Swart (2000). Each emission scenario is implemented in five different general circulation models (GCMs). Climate data for these GCM-projections are generated by downscaling the change rates of monthly mean temperatures and monthly precipitation to 0.5° resolution by bi-linear interpolation and superimposing these monthly climate anomalies (absolute for temperature, relative for precipitation and cloudiness) on the 1961-1990 average of the observed climate (for details, see Erb et al., 2009).

Considerable uncertainty exists regarding how $CO_2$ fertilization might influence future crop yields. This is due to both modelling uncertainties and to the fact that it seems likely that there are indeed interrelations between management (e.g. nutrient and water availability) and the $CO_2$ fertilization effect. To assess the range of $CO_2$ fertilization uncertainty, each of the 15 scenarios was calculated twice: first, taking into account full $CO_2$ fertilization effects according to the prescribed atmospheric $CO_2$ concentrations according to the emission scenarios

(Nakicenovic and Swart, 2000), and second, keeping atmospheric $CO_2$ concentrations constant at 370 ppm after 2000. In the latter case, yield changes are only driven by the modelled changes in precipitation and temperature, whereas in the first case the full effect of changes in temperature, precipitation and $CO_2$ levels is taken into account. Relative management levels are kept static, but sowing dates are assumed to be adapted to climate change (as described by Bondeau et al., 2007) and for wheat, maize, sunflower, and rapeseed (but not for all other crops) we assume also adaption in selecting suitable varieties.

Yield data are originally calculated at a spatial resolution of 0.5°x0.5° and then aggregated to country-level change rates. We then calculate the arithmetic mean of the change rates in all 15 scenarios with and without the $CO_2$ fertilization effect. These country-level results are then used to calculate area-weighted average changes in crop yields in each region.

## Results and discussion

Results are summarized in Table S4. The assumptions we make on diets (four variants), yields (three variants), livestock rearing systems (three variants) and cropland expansion (two variants) result in a total of 72 scenarios.

The feasibility of each scenario is classified based on a comparison of the demand for cropland and the availability of cropland resulting from each combination of assumptions. If cropland demand and availability differ by less than 5%, we classify a scenario as ‘probably feasible’; i.e. we assume that the accuracy of the biomass-balance model is too low to significantly distinguish the result from nil (yellow in Table S4). If cropland availability exceeds demand by more than 5% but less than 20% , we classify a scenario as ‘feasible’ (green in Table S4) , and blue if cropland availability exceeds demand by more than 20%. If cropland demand exceeds cropland availability by more than 5%, a scenario is classified as ‘not feasible’ (white in Table S4). Grazing area is not found to be limiting in any of the scenarios which implies that our ‘no-deforestation’ assumption does not affect the outcome of our feasibility evaluation.

Note that scenarios may be unfeasible (or undesirable) for other reasons than insufficient cropland area (i.e. impossibility to close the balance between supply and demand in our model). For example, it might be impossible to actually achieve yield levels as foreseen by the FAO for the year 2050. This might have economic reasons (e.g., lacking investment) or biophysical reasons (e.g., soil erosion, climate change, lacking water availability, too optimistic yield forecasts, etc.). Much will depend on the extent to which possible constraints can be overcome or at least mitigated through appropriate strategies for agricultural research and knowledge development, which must be seen as a complex system with a trajectory that is hard to predict (IAASTD, 2009). Feedbacks such as possible future reductions in yield levels resulting from poor management or inappropriate agricultural technologies – e.g., deterioration of soils due to unsustainable cropping practices, salinisation resulting from poor irrigation techniques, etc. – could not be considered here. Determining the infeasibility of scenarios for such reasons is outside the scope of this study.

**Table S4. Feasibility analysis of all 72 scenarios.**

| | **Crop Yields** | FAO intensive | FAO intensive | Inter-mediate | Inter-mediate | Wholly organic | Wholly organic |
|---|---|---|---|---|---|---|---|
| | **Land use change** | Massive | Business as usual | Massive | Business as usual | Massive | Business as usual |
| **DIET** | **Livestock System** | | | | | | |
| Western high meat | intensive | +/- | - | - | - | - | - |
| Western high meat | humane | - | - | - | - | - | - |
| Western high meat | organic | - | - | - | - | - | - |
| Current trend | intensive | + | + | + | +/- | - | - |
| Current trend | humane | + | + | + | +/- | - | - |
| Current trend | organic | + | +/- | +/- | +/- | - | - |
| Less meat | intensive | + | + | + | + | +/- | - |
| Less meat | humane | + | + | + | + | +/- | - |
| Less meat | organic | + | + | + | + | - | - |
| Fair less meat | intensive | ++ | + | ++ | + | +/- | +/- |
| Fair less meat | humane | ++ | + | ++ | + | +/- | +/- |
| Fair less meat | organic | ++ | + | ++ | + | +/- | - |

The table indicates which combination of assumptions on yields, land use change, characteristic of the livestock system, and diet are classified as ‘not feasible’ (blank), ‘probably feasible’ (+/- 5% cropland demand vs. availability, yellow) and ‘feasible’ (+ green and ++ blue, the latter meaning that cropland demand is <80% of cropland availability).

### *Is it possible to feed the world humanely and sustainably?*

The feasibility analysis reveals that the ’western high meat’ would require a combination of massive land use change, intensive livestock production systems and intensive use of the arable land (FAO intensive crop yields) to be classified as ‘probably feasible’.

The ’current trend’ scenario, with a global average of 3 000 kcal/cap/day and a considerable growth in the global average protein from animal products, can be realized with several different combinations of yields, livestock system and land-use change. This diet is feasible over the whole range of assumptions on the conversion efficiencies in the livestock system (intensive, humane and organic), but it clearly requires at least yield increases as assumed in the ‘intermediate’ yield assumption. Even with massive land-use change, this diet cannot be sustained in a ‘wholly organic’ yield assumption. With ‘intermediate’ yields the diet drops from the ‘feasible’ to the ‘probably feasible’ category if we move from the massive to the business as usual land-use scenario. Even with organic productivities in the livestock system, it is probably feasible to sustain such a diet but only with massive land use change if FAO intensive yields cannot be achieved.

The ’less meat’ diet assumes the same level of calorie intake as the ‘current trend’ scenario, but assumes a reduced share (-26% globally) of animal products. This demand scenario has a much broader feasibility space than the ‘current trend’ scenario. It is classified as ‘feasible’ over the whole range of assumptions on livestock system and land-use change for both FAO and intermediate yields. In addition, it was even classified as being ‘probably feasible’ in the ‘wholly organic’ yield scenario in the case of intensive and humane livestock rearing systems where it is combined with massive land-use change.

The ‘fair less meat’ diet scenario would require much lower increases in yields. It is feasible for all combinations of land-use change and livestock systems with intermediate yields, and even more so with FAO intensive crop yields. It was classified as ‘probably feasible’ with ‘wholly organic’ cropland yields for all assumptions on livestock rearing, except in the case of BAU land-use change which was not classified as being feasible in combination with the feeding efficiencies assumed in the organic livestock scenario. Of course this might change if higher yielding variants of organic cropland farming than we assume here can be developed in the future (but remember that we assume a continuation of the growth in crop yields in most regions even in that scenario, see Figure S4).

Providing enough food (not only calories, but also protein and fat) for a world with 9.2 billion inhabitants based on wholly organic cropland and livestock systems is found to be ‘probably feasible’ based on an increase of global cropland area of approximately 20%, if people adopt a diet with no more than 20% of protein from animal sources at a level of 2 800 calories per capita per day. The level of calorie intake is similar to the globally average diet in the year 2000. This diet is sufficient to provide enough food for everyone, but presumes food would be distributed equally among the global population in order to avoid malnutrition. Where crop yields are increased to even intermediate levels, substantial additional food would be available in this scenario to manage nutritional inequalities and to ensure malnourishment of a significant part of the population is avoided.

The ‘wholly organic’ assumption on crop yields is fairly radical in that it assumes that 100% of global cropland is cultivated according to organic standards. We find it reassuring that intermediate crop yields seem sufficient to support a ‘current trend’ diet, irrespective of the livestock rearing systems assumed, and highly sufficient for the ’less meat’ diet. This means that prospects are good that it will be possible to feed the world even if the high yields assumed in the ‘FAO intensive’ crop yield scenario cannot be realized. If they can, it would be possible to achieve a reasonable level of food supply based on a 50:50 mixture of organic and intensive crop agriculture or equivalent average lower yields for environmental reasons.

The feasibility analysis indicates that the additional costs of humane and organic livestock rearing systems in terms of feeding efficiency and demand for additional area seem to be relatively low. Differences in the livestock systems assumed in the scenarios played only a minor role in determining whether a scenario was feasible or not. However, the study also shows that the data uncertainties and the current limited scientific understanding of the feeding efficiency of humane farming systems demonstrate the need for better data to enable us to draw more robust conclusions on that issue.

It should also be noted that extensive livestock systems with large input-output ratios are not necessarily inefficient. The efficiency measure (input-output ratio) is based on the assumption that animal protein is the major output of livestock systems, a perspective which fails to account for the utility of livestock in less developed regions where livestock fulfils a huge range of functions besides production of protein-rich food for human consumption. In low-input agriculture, livestock is required to provide power for agriculture and transport and indispensable for the management of nutrients. A crucial function of livestock is the ability of ruminants to convert biomass not digestible by humans into food for humans, for example, biomass from waste lands or semi-deserts. Thus, livestock systems that appear to be inefficient due to their input-output ratio may in fact represent well-adapted, highly efficient production systems in their respective local contexts.

Our results imply that there is no necessity to go for the highest possible yields or maximize cropland area at all costs, irrespective of the environmental, economic, social, and health impacts involved in doing so. In contrast, our calculations suggest that the world can afford to forego some potentially possible intensification without jeopardizing world food supply.

*Bioenergy potentials*

Our results suggest that the amount of bioenergy that can be produced in a scenario grows with crop yields, cropland expansion and the efficiency of the livestock system and shrinks with the expected quantity and quality of food supply. The highest bioenergy potential (161 EJ/yr) is found in a scenario with the highly unlikely combination of FAO yields, intensive livestock system, massive land use change, and a ‘fair less meat’ diet. The lowest bioenergy potential (58 EJ/yr) is found in the only feasible scenario that succeeds in supporting the ‘western high meat’ diet.

Note that the figures on bioenergy potential we give are derived by calculating the energy content of the gross amount of biomass derived from bioenergy plants or residues. A conversion of primary biomass to final energy (e.g. a conversion of grains to liquid first generation biofuels) results in often large losses that have to be deducted when calculating the amount of final energy that can be delivered. Losses are small if biomass is used directly (without conversion), for example in cogeneration plants that deliver heat and electricity. Moreover, most of the plant material included in the gross bioenergy potentials reported here cannot be used to produce first generation biofuels. Note also that we estimate that around 10-25 EJ/yr of bioenergy were also derived from cropland and grazing areas in the year 2000. This number has to be deducted from the values gross bioenergy potentials reported here in order to calculate the additional bioenergy potential from cropland and grazing areas in 2050.

Figure S5 shows that diets have a strong effect on the total bioenergy potential. It shows the geometric mean of all ‘feasible’ and ‘probably feasible’ scenarios plus the minimum and maximum level of all scenarios within each assumption on diet. Numbers in brackets are the number for ‘probably feasible’ scenarios for each diet. The range of bioenergy potentials from cropland and grazing land (58-161 EJ/yr) we derive from our calculations is considerably lower than many studies put forward in the last years. For example, the World Energy Assessment (UNDP, 2000) reported a global technical bioenergy potential in the year 2050 between 276 and 446 EJ/yr.

If current trends with respect to diet continue (the ‘current trend’ diet) and the FAO assumption on cropland expansion is used, the bioenergy potential is estimated at 105 EJ/yr in the case of strong intensification (FAO intensive crop yields, intensive livestock), 86 EJ/yr in the case of intermediate yields and intensive livestock rearing and 79 EJ/yr in the case of intermediate yields and humane livestock rearing. Therefore there is little difference between intensive and humane livestock rearing methods in terms of impact on bioenergy potential within this model. The difference of 26 EJ/yr between the lowest and highest estimates outlined above amounts to approximately 5% of current global primary energy consumption. While this is a significant amount of energy, we feel that it would not be enough to justify a strategy of maximizing yields and efficiencies in the livestock system regardless of the environmental costs or of the amount of animal suffering that might be required to gain it. We conclude that under ‘current trend’ diet estimates, a realistic bioenergy potential on cropland and grazing land in the year 2050 may be around 70-100 EJ/yr, with the lower number being environmentally considerably more favourable than the higher one. For comparison, we note that the global technical use of primary energy is currently around 550 EJ/yr (fossil energy use around 450 EJ/yr). This means that the bioenergy potential from cropland and grazing land is in the order of magnitude of 15-22% of current fossil energy use.

Maximizing the bioenergy potentials on grazing land will require massive investments in agricultural technology, such as irrigation infrastructure, and will most probably be associated with considerable social and ecological effects, such as a further pressure on populations practising low-input agriculture. A significant risk exists that realizing these potentials might trigger indirect land use change such as deforestation in South America, Africa and Asia, because deforestation might be economically more attractive than the investments required for the intensification assumed in calculating these bioenergy potentials. This would have to be considered in policies aiming at a realization of this potential.

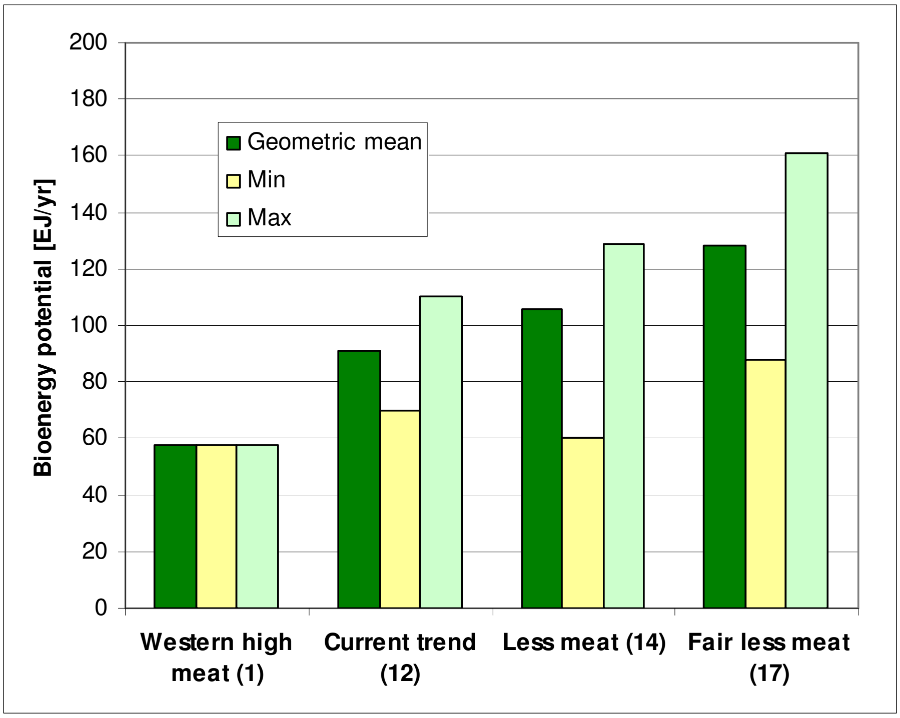


**Figure S5. Dependency of the gross bioenergy potential on assumptions on diets.**

Numbers in brackets indicate the number of scenarios classified as ‘feasible’ or ‘probably feasible for each diet’. ‘Min’ and ‘max’ represent the lowest respectively highest bioenergy potential found among these scenarios, the green bar represents the arithmetic mean of these scenarios.

Bioenergy potentials available from a ‘cascadic’ use of cropland residues (i.e. from the use of by-products from agricultural production) are considerable (21-36 EJ/yr or 18-52% of the total bioenergy potential). This biomass fraction is important for agro-ecosystems in many ways, among others for the maintenance of soil carbon, and strategies aimed at fostering its usage should be viewed cautiously. Nevertheless, our calculations reveal that this is a significant potential, which renders in-depth assessments of options to combine bioenergy production and soil fertility management (e.g., energy production through biogas production that maintains a large proportion of the nutrients and parts of the carbon) promising. Furthermore, such investigation should probably be prioritized, as the use of cascade biomass (Haberl and Geissler, 2000, WBGU, 2008) might entail only relatively limited further pressures on environmental systems, if sufficient residues are left for the maintenance of soil fertility.

The study shows that links between diets and the agricultural production technology have massive effects on the availability of bioenergy in the future. Calculations which do not take such interlinkages into account have to remain almost meaningless. Moreover, vital and decisive uncertainties related to the effects of climate change make assumptions on future agricultural production highly uncertain.

*Land-use intensity*

The scenarios differ not only with regard to their bioenergy potential, but also with regard to the level of environmental pressure exerted on the world's terrestrial ecosystems. A full assessment of these pressures is beyond the scope of this study. However, one output of our calculations – i.e., grazing intensity – can give some indication of the amount of environmental pressure associated with each scenario, as discussed in this section. Grazing intensity is defined as the ratio between biomass harvested on grazing areas to the amount of annual aboveground biomass production ($aNPP_{act}$) on grazing areas yields the indicator grazing intensity.

Environmental impacts of grazing often grow with the intensity of grazing. In particular, overgrazing can have severe ecological impacts such as soil and ecosystem degradation, negative impacts on biodiversity or loss of valuable habitats. It may also result in social conflicts. These adverse impacts can at least to some extent be mitigated through appropriate management, but doing so will require substantial levels of investment.

Figure S6 shows that grazing intensity is significantly different between the four diet scenarios (left, blue columns) if it is not assumed that the bioenergy potential on grazing areas will be actually realized. Grazing intensity declines as calorie inputs and the share of animal products in the diet is assumed to be reduced.

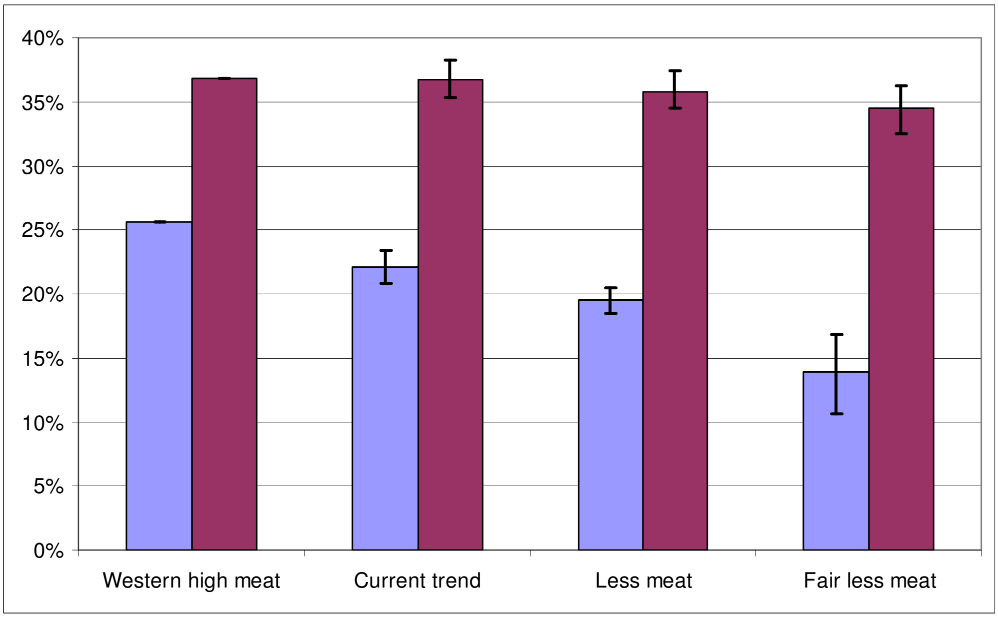


**Figure S6. NPP harvested as percentage of aboveground $NPP_{act}$ on grazing areas: the left (blue) bars indicate grazed biomass, the right (purple) bars indicate grazed biomass plus biomass produced for energy supply on grazing areas.**

If it is assumed that the bioenergy potentials on grazing areas are realized, however, the differences between the scenarios become very small (Figure S6, right, purple columns). These purple columns are calculated assuming that grazing areas do not only supply the amount of feed required in each scenario, but that the full extent of the bioenergy potential on grazing areas assumed to exist in each scenario is also realized and the respective amount of biomass is harvested for bioenergy production. In that case, all four diet scenarios are characterized by a land-use intensity on grazing areas of around 35%. This is considerably higher than the value observed in the year 2000 (19%; Haberl et al., 2007). We take this as an indication that the realization of the bioenergy potentials identified in this study, in particular of the bioenergy potentials that depend on bioenergy crops grown on cropland or grazing areas, might have significant environmental impacts that should be well considered before actually embarking on a large-scale realization of these potentials.

*What could be the potential impact of climate change?*

We find that the effect of climate change on yields on cropland is highly uncertain. In particular, we find that the impact of climate change on yields can be strongly negative if the $CO_2$ fertilization effect is not taken into account, whereas it can be strongly positive if it is assumed to be fully effective (Table S5). The $CO_2$ fertilization effect results from the fact that plants take up atmospheric $CO_2$ for photosynthesis. Higher $CO_2$ levels can therefore, under certain circumstances (sufficient nutrient supply), boost plant growth and alleviate water stress. However, while detectable under controlled (laboratory) conditions, the magnitude of this effect under real world conditions is still uncertain.

The effect of these yield changes on the feasibility of the 72 scenarios is large. If we neglect $CO_2$ fertilization, only 34 of the 72 scenarios would be at least ‘probably feasible’. If we assume the full $CO_2$ fertilization effect, 62 of the 72 scenarios would be at least ‘probably feasible’. In the latter case, the ‘wholly organic’ yield scenario combined with organic livestock would probably even deliver the ’current trend’ diet (if we assume massive expansion of cropland). By contrast, ‘wholly organic’ crop yields would not be sufficient for any diet in the absence of $CO_2$ fertilization.

**Table S5. Modelled climate impact on cropland yields in 2050 with and without $CO_2$ fertilization.**

| | Mean yield change under climate change 2050 | |
|---|---|---|
| | with $CO_2$ fertilisation | without $CO_2$ fertilisation |
| Northern Africa and Western Asia | + 4.44 % | - 8.65 % |
| Sub-Saharan Africa | + 8.46 % | - 6.17 % |
| Central Asia and Russian Federation | + 24.91 % | + 5.12 % |
| Eastern Asia | + 11.96 % | - 3.90 % |
| Southern Asia | + 18.45 % | - 15.61 % |
| South-Eastern Asia | + 28.22 % | - 15.83 % |
| Northern America | + 12.45 % | - 6.25 % |
| Latin America & the Carribean | + 12.39 % | - 7.02 % |
| Western Europe | + 16.42 % | + 2.04 % |
| Eastern & South-Eastern Europe | + 19.08 % | - 0.66 % |
| Oceania and Australia | + 0.74 % | - 16.02 % |

Note that we could not model possible feedbacks between management and climate impact, even though it is clear that such feedbacks might be highly relevant. Our analysis suggests that the possible impact of climate change may be substantial, but is still highly uncertain. The extent to which climate change might change the feasibility of feeding the world sustainably cannot be evaluated reliably at present. It is nevertheless encouraging that our calculations indicate that the global agricultural system would probably be able to deliver a ‘current trend’ diet with intermediate yield levels, even if the impact of climate change on yields should be negative.

## Conclusions and policy recommendations

*Diets*

**Conclusion:** Our findings strongly underline the view that the share of animal products in human diets has a strong effect on environmental impact, the possibility to produce animal products humanely or through organic livestock rearing.

**Recommendation:** Any effective measures to reduce the level of consumption of animal products (including those derived from eggs and milk) are beneficial in terms of environmental impacts, animal welfare, biodiversity, and bioenergy potential.

*Organic agriculture*

**Conclusion:** We provide evidence that organic agriculture can probably feed a world population of 9.2 billion in 2050, if relatively modest diets are adopted, where a low level of inequality in food distribution is required in order to avoid malnutrition. This conclusion is based on the best currently available data on system-wide yield levels of organic cropland agriculture as compared to intensive crop production systems. If agricultural research were to succeed in developing higher-yielding variants of organic agriculture, richer diets based on organic agriculture could be achieved. Judging to what extent this is feasible is beyond the scope of this study. We clearly show that the extent to which foreseen diet trajectories have to be modified towards less rich diets strongly depends on the ability to reach higher yields in organic or environmentally less demanding agriculture.

**Recommendation:** We therefore recommend to direct research and technical development towards agricultural practices that follow organic standards or are otherwise environmentally less destructive and are nevertheless able to achieve high yield levels.

*Humane and environmentally friendly farming*

**Conclusion:** We provide strong evidence that neither humane livestock rearing systems nor environmental objectives in cropland farming should be discarded based on claims that these practices would jeopardize food security. To the contrary, we did not find a strong effect on the feasibility of scenarios of feeding efficiencies and the additional area demand of free-range systems for monogastric species associated with humane or even organic livestock rearing standards. While a transition to wholly organic cropland agriculture (100% of the area planted according to organic standards) seems to be challenging in terms of the changes in diets and the need for an equitable distribution of food in such a scenario, we find that even the intermediate yield scenario (that might, for example, be achieved by organic agriculture on 50% of the area, if the other 50% were as intensively cultivated as foreseen by the FAO) would be able to deliver a ‘current trend’ diet in 2050.

**Recommendation:** We therefore recommend a continuation of support for organic and other environmentally benign agricultural management practices, while at the same time trying to optimize yields and efficiencies without adopting unsustainable or inhumane technologies and practices. Our calculations suggest that there is no need to boost yields and efficiencies regardless of the costs in terms of environmental pressures and animal welfare.

*Bioenergy*

**Conclusion:** Expectations with respect to future bioenergy potentials should be lowered to more realistic levels. Our study provides strong evidence that explicit consideration of roughage demand of livestock to be covered on grazing areas has a significant effect on the bioenergy potential in 2050. The range of bioenergy potentials from cropland and grazing land identified here is considerably lower than many studies put forward in the last years. Moreover, we find that future diets have a strong effect on the size of the bioenergy potential. Under 'business-as-usual' assumptions on diets, the bioenergy potential on cropland and grazing land is in the order of magnitude of 100 EJ/yr, including the bioenergy currently produced on these areas.

**Recommendation:** Sustainability issues involved in strategies aiming at a promotion of bioenergy need to be taken seriously. The integrated optimization of food, fibre and bioenergy supply ('cascade utilization of biomass') is an important element of any sustainable bioenergy strategy. Area demand of bioenergy – as well as of all other renewable energies – should be considered highly important when judging the relative merits of different renewable energy (bioenergy) technologies. First generation biofuels perform particularly poorly with respect to that criterion. The combustion of solid biomass in combined heat and power (cogeneration) plants is probably much more favourable in terms of energy efficiency. Environmental issues associated with bioenergy, in particular of dedicated bioenergy crops, should be evaluated carefully before pushing these technologies on a grand scale.

## Need for additional research

More detailed research is required on system-level efficiencies of different livestock rearing systems and *ceteris-paribus* (everything else kept constant) comparisons of cropland yields in industrialised and organic agriculture. While we feel reasonably certain that these uncertainties probably do not affect the main recommendations formulated above, but more research into these issues would be helpful in order to better understand the interrelations and feedbacks in the global food and agriculture system.

A combination of the modelling strategy pursued here (based on calculating consistent biomass balances, i.e. the socioeconomic metabolism approach) could gain a lot if combined or even integrated with traditional methods based on economic modelling and / or ecosystem modelling (e.g. vegetation models). Research in that direction would help to better understand the dynamics of coupled global social-economic-ecological systems that is at the heart of the global sustainability challenge.

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# Introduction

The surging demand of a growing and increasingly affluent world population for food, fibre, and energy is confronting the earth's terrestrial ecosystems with mounting pressures. Already today, land use is degrading the ability of ecosystems to deliver vital services to humanity (Millennium Ecosystem Assessment, 2005). Changes in the earth's land system are a pervasive driver of global environmental change (GLP, 2005, Turner et al., 2007). Land-use change often leads to biodiversity loss, changes in runoff, declining buffering capacities of ecosystems, greenhouse gas (GHG) emissions, soil and ecosystem degradation and many more adverse effects (Foley et al., 2005).

Feeding and fuelling the world sustainably, fairly and humanely in the next decades is one of the greatest challenges humanity is currently facing (Kahn et al., 2009). This study is motivated by the goal of contributing to our understanding of that challenge in the face of growing concerns about the sustainability of global agricultural and food systems. While modern agricultural technologies have resulted in strong increases in yields and agricultural efficiencies in general, they have also, in many cases, caused significant and widespread negative environmental effects, including degradation of land, ecosystems, freshwater, ocean and atmospheric resources (IAASTD, 2009).[1]

This study is intended as an exploratory analysis of the trade-offs and interrelations between several objectives:

- Feeding the world fairly; that is, reducing or even eradicating the stark contrast between malnourishment and even hunger in poor regions and overconsumption of unhealthy food (too much meat, fat and sugars) in wealthier regions.
- Increasing the sustainability of biomass provision by adopting practices of organic farming, with respect to both plant and animal production.
- Reducing the amount of animal suffering through adoption of humane farming methods (e.g. Arey and Brooke, 2006); such practices have significant potential to improve animal welfare, for example through allowing them to range freely.
- Providing plant biomass for energy provision as a substitute for fossil fuels if it can be sustainably produced and effectively reduces greenhouse gas (GHG) emissions.
- Protecting areas of high biodiversity value such as pristine tropical forests.

These goals have to be seen in the context of the following global trajectories:

- The growth in global population numbers is bound to increase the total human consumption of biomass for food and fibre.
- Growing affluence and attempts at eradicating world hunger and improving human diets in poor countries will further push up biomass demand.
- Climate change may have substantial and as yet largely unknown or at least highly uncertain consequences for agriculture and forestry.

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[1] The IAASTD (International Assessment of Agricultural Knowledge, Science and Technology for Development) was sponsored by various UN organizations and many governments. It involved a 4 year discussion processes including about 400 scientists, two rounds of peer-review and participation of many government and other experts. The Global Summary for Decision Makers of IAASTD was approved by 58 governments at the Intergovernmental Plenary Session in Johannesburg, South Africa in April, 2008. The full IAASTD report was published by Island Press in 2009.

Fully studying the above-mentioned goals in the context of these challenges is as yet impossible, as none of the global integrated assessment models such as IMAGE (see e.g., Alcamo et al., 1996; Bouwman et al., 2006) incorporates sufficient detail on farming practices or biomass utilization pathways as would be needed to answer these questions and to analyze all the feedbacks that have to be understood in that context.

We aim to outline the magnitude of the challenges based on a data-driven approach. We base our investigation on a solid, data-based understanding of global socioeconomic biomass flows, land use and the human appropriation of net primary production (HANPP) in the year 2000 (Erb et al., 2007, Haberl et al., 2007, Krausmann et al., 2008a). From there, we construct scenarios for the situation around 2050, based on a suite of estimates of population growth, diets, agricultural technology, etc., as explained below in detail.

In elaborating the scenarios, we considered one population forecast (the UN medium variant) and one scenario of the growth of urban areas. As a starting point we used the FAO study ‘World agriculture towards 2030/2050’ (FAO, 2006b) which we assume to be a prominent ‘business-as-usual’ scenario that describes a strong intensification trajectory and is optimistic in terms of future yields. We then constructed a biomass-balance model that allows us to build consistent scenarios of supply and demand of biomass based on a consistent set of data for 2050 on:

- Cropland and grazing area
- Biomass yields on cropland and palatable biomass production on grazing land
- Feed conversion efficiencies for livestock
- Conversion losses in the biomass flow chain from production to final consumption.

The main job of the biomass-balance model is that it calculates a consistent global biomass flow balance from production to final consumption, based on area availability and various assumptions on diets, efficiencies, yields, etc. as explained below.

In interpreting the following analyses it is important to remember that this is a scoping study. In many cases, data were lacking to build the calculations on more than educated estimates. So the study results should be taken as fuel for thought and discussion that demonstrate what the world might look like if our assumptions are correct. We will clearly flag where our work is based on solid statistical data, on less solid data from statistics, modelling or other sources, on anecdotal evidence, or judgement using our expertise. Readers are invited to help improve these analyses by contributing new data, estimates or assumptions or to use our calculations for their own modelling and scenario work. We will be grateful for any suggestions on how to further improve this work. The focus of this study is on biophysical aspects of land use and biomass utilization (including cropland farming, livestock rearing, bioenergy production, and conversion of primary biomass to main final products). Social, institutional, economic and political factors that influence decisions on production, consumption (above all diet), land use, choice of technology, etc., are outside the scope of this study.

# Data and methods

## Definition of study regions and biomass aggregates

This study is carried out on the level of 11 world regions as shown in Figure 1 and defined in Table A 1 in the Appendix. The regional grouping we use is based on the classification of the macro-geographical (continental) regions and geographical sub-regions as defined by the United Nations Statistical Division (UNSD, 2006).

Table 1 describes the world regions in terms of area, population density, GDP, land use and other indicators. Population density is lowest in Oceania and Australia with only 3.5 inhabitants per km$^2$ and highest in South Asia with over 200 inhabitants per km$^2$. Population density is an important indicator of resource endowment (land availability) that has been shown to have a strong impact on land-use systems. The land-use systems of regions with a high population are considerably more area-efficient than those with low population density (Krausmann et al., 2009). Whether a region is a net exporter or net importer of land-based products is determined by population density rather than development status (Erb et al., 2009). Per-capita GDP in constant 1990 US$ is lowest in South Asia (585 US$/cap) and highest in North America with almost 28 000 US$/cap. The percentage of rural population is an important development indicator because it declines consistently during the transition from an agrarian to the industrial mode of subsistence (Fischer-Kowalski and Haberl, 2007, Krausmann et al., 2008b). It is lowest in Western Europe (21%) and highest in South Asia (71%). Fertilizer use and livestock density are indicators of land-use intensity and differ strongly with population density as well as with development status (see Table 1 and Krausmann et al., 2009). The percentage of the total land area in each region used as cropland or grazing area is also indicative of land-use intensity and shows considerable differences among world regions.

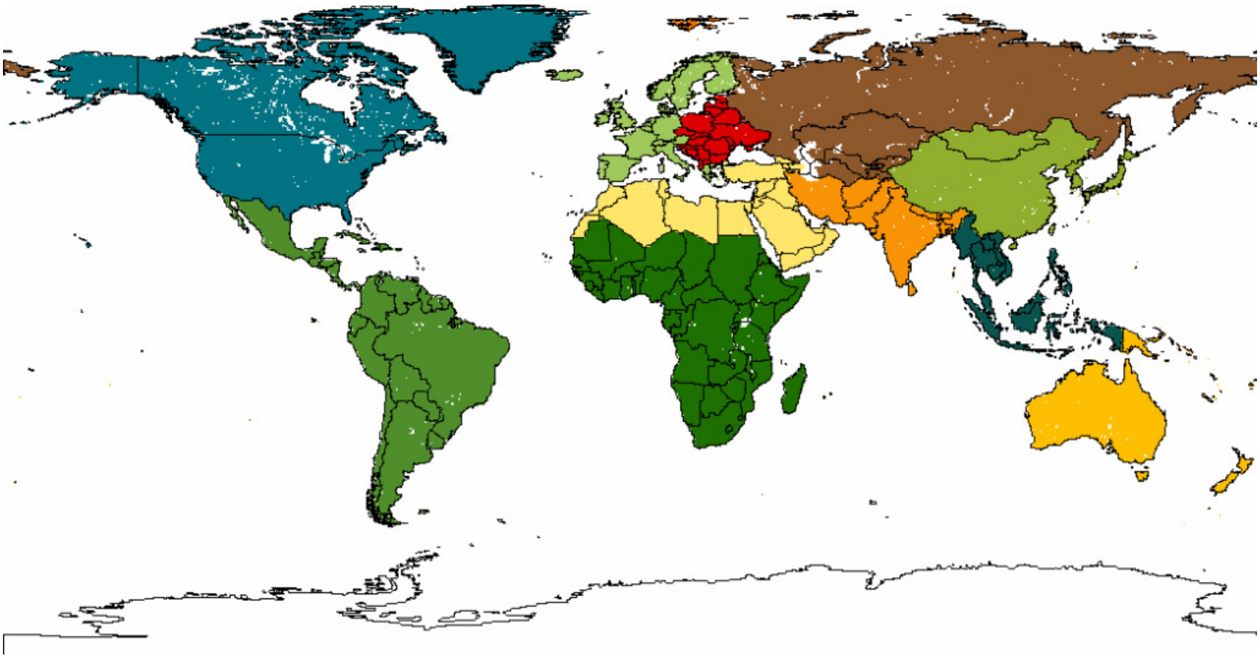
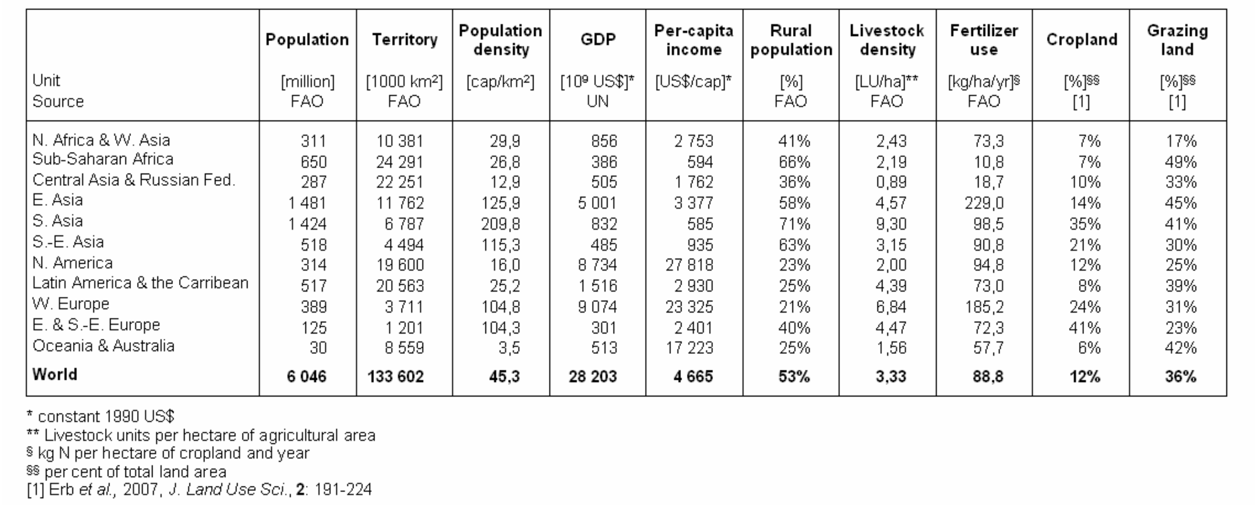


**Figure 1. World regions used in this study**

**Table 1. Description of the study regions in terms of area, population density, land use and other indicators.**



| | Population | Territory | Population density | GDP | Per-capita income | Rural population | Livestock density | Fertilizer use | Cropland | Grazing land |
|---|---|---|---|---|---|---|---|---|---|---|
| Unit<br>Source | [million]<br>FAO | [1000 km$^2$]<br>FAO | [cap/km$^2$] | [10$^9$ US$]*<br>UN | [US$/cap]* | [%]<br>FAO | [LU/ha]**<br>FAO | [kg/ha/yr]§<br>FAO | [%]§§<br>[1] | [%]§§<br>[1] |
| N. Africa & W. Asia | 311 | 10 381 | 29,9 | 856 | 2 753 | 41% | 2,43 | 73,3 | 7% | 17% |
| Sub-Saharan Africa | 650 | 24 291 | 26,8 | 386 | 594 | 66% | 2,19 | 10,8 | 7% | 49% |
| Central Asia & Russian Fed. | 287 | 22 251 | 12,9 | 505 | 1 762 | 36% | 0,89 | 18,7 | 10% | 33% |
| E. Asia | 1 481 | 11 762 | 125,9 | 5 001 | 3 377 | 58% | 4,57 | 229,0 | 14% | 45% |
| S. Asia | 1 424 | 6 787 | 209,8 | 832 | 585 | 71% | 9,30 | 98,5 | 35% | 41% |
| S.-E. Asia | 518 | 4 494 | 115,3 | 485 | 935 | 63% | 3,15 | 90,8 | 21% | 30% |
| N. America | 314 | 19 600 | 16,0 | 8 734 | 27 818 | 23% | 2,00 | 94,8 | 12% | 25% |
| Latin America & the Carribean | 517 | 20 563 | 25,2 | 1 516 | 2 930 | 25% | 4,39 | 73,0 | 8% | 39% |
| W. Europe | 389 | 3 711 | 104,8 | 9 074 | 23 325 | 21% | 6,84 | 185,2 | 24% | 31% |
| E. & S.-E. Europe | 125 | 1 201 | 104,3 | 301 | 2 401 | 40% | 4,47 | 72,3 | 41% | 23% |
| Oceania & Australia | 30 | 8 559 | 3,5 | 513 | 17 223 | 25% | 1,56 | 57,7 | 6% | 42% |
| **World** | **6 046** | **133 602** | **45,3** | **28 203** | **4 665** | **53%** | **3,33** | **88,8** | **12%** | **36%** |

* constant 1990 US$
** Livestock units per hectare of agricultural area
§ kg N per hectare of cropland and year
§§ per cent of total land area
[1] Erb *et al.*, 2007, *J. Land Use Sci.*, **2**: 191-224

We used the following aggregates when working with biomass production and consumption flows. We distinguished the following food aggregates:

- Cereals
- Roots and tubers
- Sugar crops
- Pulses
- Oil crops
- Vegetables and fruits
- Meat of ruminants (grazers)
- Milk, butter and other dairy products
- Meat of pigs, poultry and eggs
- Fish
- Other crops

We distinguished the following food crop groups:

- Cereals: Wheat, rice, maize, rye, barley and others
- Oil-bearing crops: Soybean, sunflower, rape seed, coconuts, palm oil and others
- Sugar crops: Sugar cane and sugar beet
- Pulses: Beans, lentils, peas and others
- Roots and tubers: Potatoes, cassava, yams and others
- Vegetables and fruits
- Others, including tobacco, tea, coffee, cotton and others.

We distinguished the following groups of livestock:

- Grazers (mostly ruminants): cattle, sheep, goats and others
- Non-grazers: pigs, poultry and other animals not able to digest roughage (feed derived from plant parts rich in cellulose and other fibres, e.g. straw or grasses).

Data from FAO or other sources were aggregated to these categories for all analyses. Data reported in fresh weight or air-dry weight were converted into dry matter using specific data on water content according to standard tables of food and feed composition (Souci et al., 2000, Purdue University Center for New Crops and Plant Products, 2006, Löhr, 1990, Watt and Merrill, 1975).

## Global land use and biomass flow data for the year 2000

The analysis presented in this study is based on an extensive database for the year 2000 that consistently integrates land use and global socioeconomic data as well as data on ecological biomass flows across a wide range of spatial scales, from high-resolution datasets (available at 5' geographic resolution, i.e. about 10x10 km at the equator, covering ~98% of the earth's land excluding Antarctica) to the country level ( ~160 countries) and the level of the above-described eleven world regions. These databases were constructed in previous and ongoing projects mostly funded by the Austrian Science Funds (FWF, www.fwf.ac.at). Most of the data can be downloaded freely (http://www.uni-klu.ac.at/socec/inhalt/1088.htm) and have been extensively discussed in various articles (Erb et al., 2007, Haberl et al., 2007, Krausmann et al., 2008a). We here provide an overview of the methods used to assess these data and of the main results according to the 11 study regions used in this study that were used to construct the biomass balance model.

The main strength of our database is that it covers three large domains of data that have been cross-checked against one another and are consistent between scales (grid and country level) and domains (net primary production or NPP, biomass harvest and byflows, livestock, biomass processing and use). The three main accounts are:

- A geographically explicit (5' geographic resolution, i.e. approximately 10x10 km at the equator) land-use dataset (Erb et al., 2007). Cropland area and forest area are consistent with FAO data on cropland (FAO, 2004) and the large forest resource assessments FRA and TBFRA (UN, 2000, FAO, 2004) on the country level. Grazing land is classified according to its suitability for grazing, distinguishing 4 classes (class 1 denoting the best suited, class 4 the least suited grazing areas).The dataset was cross-checked extensively against other global and regional datasets (see Erb et al., 2007).
- A geographically explicit (5' geographic resolution, i.e. approximately 10x10 km at the equator) assessment of the global human appropriation of net primary production (HANPP, see Haberl et al., 2007). NPP is the amount of biomass produced by green plants through photosynthesis, net of the energy required by the plant for their own metabolism. HANPP is an indicator of land-use intensity defined as the difference between the amount of NPP that would remain in the ecosystem in the absence of land use and the amount of NPP that remains in the ecosystem after human harvest

(Vitousek et al., 1986, Wright, 1990, Haberl, 1997).[2] The rationale behind HANPP is that it assesses changes in trophic energy flows in ecosystems that are relevant for carbon and nutrient cycling, the water balance, ecosystem functions and services as well as biodiversity. The above-cited HANPP assessment is based on a global database that includes, for each grid cell, the following parameters: $NPP_0$, i.e. the net primary production of potential vegetation, the vegetation that would exist in the absence of human intervention; $NPP_{act}$, i.e. the NPP of the currently prevailing vegetation; and $NPP_h$, i.e. the biomass harvested by humans, grazed by their livestock or destroyed during harvest or by human-induced fires (the latter are available on the country level only, for the most recent estimates see Lauk and Erb, 2009).

- A country-level assessment of socioeconomic biomass use that traces biomass flows from harvest to final consumption (Krausmann et al., 2008a). This dataset is based on FAO statistics and estimates flows not covered in statistics (e.g., grazing of livestock) based on country-level feed balances of all major livestock species. Livestock feed balances were cross-checked against the productivity of grazing areas as part of the above-cited HANPP assessment (see Haberl et al., 2007, supporting online material). Biomass harvest from cropland and permanent cultures, including primary crops, used and unused crop-residues was calculated from the FAO agricultural production database (FAO, 2004).

Data on land use in the year 2000 are presented in Table 2. This dataset was extensively cross-checked against statistical data and data derived from remote sensing (for reference see Erb et al., 2007). According to this dataset, 75.5% of the earth's land (excluding Greenland and Antarctica) is already under human use which, however, ranges from very intensive to very extensive use. Approximately 1% of the land is used as infrastructure and urban area, 11.7% as cropland, 26.8% as forestry land, 36.0% as grazing land. Grazing land is characterized by four quality classes (1-4, with 1 denoting the best grazing land and 4 the worst). Grazing land includes a large variety of ecosystem types – it comprises intensively cultivated meadows as well as barely productive semi-natural landscapes. It can be of very high ecological value.

Of the remaining 24.5%, about one half is completely unproductive, often covered by rocks and snow or deserts with an aboveground productivity below 20 g $C/m^2/yr$ (denoted as 'non-productive land' in Table 2). The other half, denoted as 'unused productive land' includes the world's last pristine forests (a bit over 6 million $km^2$, 4.6% of total area), including tropical rainforests as well as all other forests with almost no signs of human use (as defined by Sanderson et al., 2002), most of which are in boreal regions. This category, however, also includes pretty unproductive ecosystems such as arctic or alpine tundras and grasslands. As a result, it seems highly unlikely that currently unused land can contribute significantly to future biomass production, with the possible exception of pristine forests. The latter, however, should be excluded from use for two reasons: (a) using this land would result in massive carbon losses and therefore GHG emissions and (b) pristine forests are among the most valuable ecosystems from the point of view of nature conservation. We therefore explicitly excluded pristine forests from our analysis.

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[2] HANPP can be defined as $NPP_0 - NPP_t$ (ecological perspective) or as the sum of change in productivity resulting from land conversion ($\Delta NPP_{LC}$) and harvest ($NPP_h$), i.e. from a societal perspective. Both definitions give identical results. Explanations of acronyms see text.

**Table 2. Land use in the 11 study regions in the year 2000**

| | Infra-structure | Cropland | Forestry | Grazing land | Non-productive land | Unused productive land | Total |
|---|---|---|---|---|---|---|---|
| | | | | [mio. km$^2$] | | | |
| N. Africa and W. Asia | 0.042 | 0.763 | 0.268 | 1.738 | 7.421 | 0.047 | 10.279 |
| Sub-Saharan Africa | 0.111 | 1.781 | 5.828 | 11.867 | 3.443 | 0.945 | 23.975 |
| Central Asia and Russian Fed. | 0.189 | 1.572 | 7.155 | 6.742 | 0.280 | 4.494 | 20.432 |
| E. Asia | 0.140 | 1.604 | 2.121 | 5.146 | 2.075 | 0.448 | 11.533 |
| S. Asia | 0.113 | 2.305 | 0.850 | 2.554 | 0.824 | 0.024 | 6.670 |
| S.-E. Asia | 0.039 | 0.931 | 2.098 | 1.331 | 0.000 | 0.083 | 4.483 |
| N. America | 0.337 | 2.240 | 4.741 | 4.473 | 1.549 | 5.169 | 18.508 |
| Latin America, the Carribbean | 0.064 | 1.685 | 8.733 | 7.932 | 0.256 | 1.624 | 20.295 |
| W. Europe | 0.198 | 0.862 | 1.318 | 1.130 | 0.011 | 0.136 | 3.655 |
| E. & S.-E. Europe | 0.103 | 0.941 | 0.630 | 0.482 | 0.000 | 0.002 | 2.158 |
| Oceania and Australia | 0.023 | 0.540 | 1.216 | 3.484 | 0.305 | 2.817 | 8.385 |
| World | 1.360 | 15.225 | 34.958 | 46.881 | 16.163 | 15.788 | 130.375 |

Source: Erb et al., 2007.

Human activities already have a significant impact on global biomass flows in ecosystems. Table 3 gives an overview on the human appropriation of aboveground net primary production in the year 2000. We here report only aboveground data, as the belowground fraction is barely, if at all, accessible for human use (which is the primary question discussed in this study). $aNPP_0$ is the aboveground productivity of potential vegetation, $aNPP_{act}$ the aboveground productivity of the currently prevailing vegetation, $aNPP_h$ is the amount of aNPP harvested by humans and $aNPP_t$ the amount of biomass remaining in ecosystems after harvest. Table 3 shows that human activities such as the conversion of pristine ecosystems into urban areas, cropland and pasture and the soil degradation resulting from such processes have resulted in a reduction of the productivity of vegetation of originally 70.8 billion tons of dry matter biomass per year (Gt/yr) to 67.1 Gt/yr (-5%). In addition, humans harvest 14.1 Gt/yr, resulting in a total aHANPP of 17.7 Gt/yr or 25% of $aNPP_0$. Note that human-induced fires are not included in these data. The best currently available estimates indicate that human-induced fires consume about 3.5-3.9 Gt/yr (Lauk and Erb, 2009), bringing the total amount of $NPP_h$ to 21.2-21.6 Gt/yr which means that total aHANPP is about 30% of $aNPP_0$. In other words, human activities have already reduced the amount of NPP remaining available in terrestrial ecosystems for all animals not cultivated by humans as well as all other heterotrophs (e.g., fungi and microorganisms) by 30%. The data presented in Table 3 are available on the level of grid cells and above (e.g. on the country level) and can be broken down to the land-use classes presented in Table 2.

**Table 3. The human appropriation of aboveground net primary production (aHANPP) in the year 2000**

| | $aNPP_0$ | $aNPP_{act}$ | $aNPP_h$* | $aNPP_t$* | aHANPP* | aHANPP* |
|---|---|---|---|---|---|---|
| | [billion tons of dry matter biomass per yr = Gt/yr] | | | | | [%] |
| Northern Africa and Western Asia | 0.779 | 0.813 | 0.343 | 0.471 | 0.308 | 40% |
| Sub-Saharan Africa | 14.564 | 13.090 | 1.634 | 11.457 | 3.108 | 21% |
| Central Asia and Russian Federation | 8.935 | 8.324 | 0.495 | 7.829 | 1.106 | 12% |
| Eastern Asia | 4.513 | 4.815 | 2.188 | 2.627 | 1.886 | 42% |
| Southern Asia | 2.582 | 2.792 | 1.886 | 0.906 | 1.676 | 65% |
| South-Eastern Asia | 5.087 | 4.407 | 1.020 | 3.387 | 1.700 | 33% |
| Northern America | 8.761 | 8.584 | 1.971 | 6.614 | 2.147 | 25% |
| Latin America, the Carribbean | 17.911 | 16.903 | 2.433 | 14.469 | 3.442 | 19% |
| Western Europe | 2.275 | 2.404 | 1.178 | 1.226 | 1.049 | 46% |
| Eastern & South-Eastern Europe | 1.509 | 1.263 | 0.556 | 0.707 | 0.802 | 53% |
| Oceania and Australia | 3.836 | 3.723 | 0.384 | 3.339 | 0.497 | 13% |
| World | 70.753 | 67.119 | 14.088 | 53.031 | 17.721 | 25% |

* Excluding human-induced fires. The current best available estimate for the amount of NPP annually consumed in human-induced fires is 3.5-3.9 billion tons of dry-matter biomass (Lauk and Erb, 2009). If human-induced fires are included, aHANPP rises to 21.2-21.6 Gt/yr, i.e. around 30% of $aNPP_0$.
Source: updated from Haberl et al., 2007.

A summary of the global biomass flow dataset underlying this study is given in Table 4 and Table 5. These data were derived from various FAO statistics as explained in detail in Krausmann et al. (2008a). Data are consistent with the above-cited HANPP assessment (Table 3) and the global land-use dataset presented in Table 2.

Biomass supply and demand varies strongly between different regions. For example, harvest of primary crops varies between 0.3 and 1.5 t/cap/yr (metric tons per capita and year), with the highest values found in sparsely populated industrialised regions such as North America or Oceania and Australia. As might be expected, the use of plant biomass for direct human consumption varies a lot less (between 0.16 and 0.29 t/cap/yr). The use of biomass as market feed and non-market feed, however, varies strongly.[3] For example, the amount of market feed used may be as low as 0.03 t/cap/yr in South Asia, but also as high as 0.65 t/cap/yr in North America. The amount of non-market feed is lowest in South-East Asia (0.39 t/cap/yr) and highest in Oceania at over 20 times that value (8.54 t/cap/yr). These data thus underline the enormous importance of the livestock sector for global biomass supply and demand: Non-market feed amounts to 50% of global biomass demand. Livestock consumes another 8% as market feed. In other words, livestock consumes 58% of all global plant biomass demand. Direct human consumption (12%) and wood (16%) are comparably small biomass flows.

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[3] The distinction between market feed and non-market feed is, in principle, based on the criterion whether feed is produced by the farm that keeps the animals or whether it is bought on the market. We here distinguish these two categories by grouping crops or by-products that are used as feed and are usually self-produced as 'non-market feed' and those that are mostly traded (above all cereals, maize, etc.) as 'market feed'. Market feed is always produced on cropland, whereas non-market feed includes grazing and mowing on grazing land as well as some crops that are usually not traded (e.g., crop residues, maize for silage, fodder beets, some leguminous crops).

**Table 4. Plant biomass supply of the 11 world regions per capita and year**

| | Net import agric. biomass | Wood import | Harvest primary crops | Harvest fodder crops | Harvest crop residues | Grazed biomass | Wood harvest |
|---|---|---|---|---|---|---|---|
| | | | | [t dry matter / cap /year] | | | |
| N. Africa & W. Asia | 0.190 | 0.037 | 0.313 | 0.060 | 0.336 | 0.296 | 0.084 |
| Sub-Saharan Africa | 0.022 | 0.000 | 0.282 | 0.007 | 0.453 | 0.937 | 0.557 |
| Central Asia & Russian Fed. | 0.015 | 0.000 | 0.346 | 0.184 | 0.356 | 0.207 | 0.261 |
| E. Asia | 0.053 | 0.049 | 0.378 | 0.011 | 0.352 | 0.293 | 0.116 |
| S. Asia | 0.004 | 0.003 | 0.303 | 0.015 | 0.385 | 0.421 | 0.169 |
| S.-E. Asia | 0.000 | 0.000 | 0.501 | 0.003 | 0.491 | 0.208 | 0.366 |
| N. America | 0.000 | 0.000 | 1.426 | 0.569 | 1.142 | 0.925 | 1.159 |
| Latin America, the Carribbean | 0.000 | 0.000 | 0.647 | 0.081 | 0.785 | 2.205 | 0.507 |
| W. Europe | 0.091 | 0.051 | 0.666 | 0.293 | 0.441 | 0.767 | 0.365 |
| E. & S.-E. Europe | 0.000 | 0.000 | 1.154 | 0.483 | 1.118 | 0.195 | 0.571 |
| Oceania & Australia | 0.000 | 0.000 | 1.485 | 2.003 | 1.124 | 6.023 | 1.106 |
| World | 0.000 | 0.001 | 0.473 | 0.094 | 0.485 | 0.634 | 0.321 |

Source: Krausmann et al., 2008a

**Table 5. Plant biomass use of the 11 world regions per capita and year**

| | Food | Market feed | Seed | Other use | Non market feed* | Fire wood | Indust. wood | Waste, losses | Net export agric. | Net export wood |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | [t dry matter / cap /yr] | | | | | |
| N. Africa & W. Asia | 0.288 | 0.130 | 0.015 | 0.180 | 0.544 | 0.066 | 0.055 | 0.038 | 0.000 | 0.000 |
| Sub-Saharan Africa | 0.211 | 0.035 | 0.006 | 0.173 | 1.232 | 0.501 | 0.047 | 0.043 | 0.000 | 0.008 |
| Central Asia, Russ. Fed. | 0.155 | 0.140 | 0.050 | 0.264 | 0.493 | 0.102 | 0.074 | 0.007 | 0.000 | 0.085 |
| E. Asia | 0.259 | 0.133 | 0.008 | 0.192 | 0.482 | 0.080 | 0.086 | 0.013 | 0.000 | 0.000 |
| S. Asia | 0.240 | 0.031 | 0.014 | 0.031 | 0.798 | 0.159 | 0.013 | 0.013 | 0.000 | 0.000 |
| S.-E. Asia | 0.292 | 0.070 | 0.007 | 0.329 | 0.394 | 0.290 | 0.046 | 0.067 | 0.043 | 0.029 |
| N. America | 0.271 | 0.654 | 0.025 | 0.955 | 1.718 | 0.247 | 0.825 | 0.074 | 0.365 | 0.087 |
| Latin America, Carribb. | 0.239 | 0.168 | 0.008 | 0.180 | 2.945 | 0.346 | 0.155 | 0.094 | 0.085 | 0.006 |
| W. Europe | 0.239 | 0.401 | 0.016 | 0.339 | 1.225 | 0.084 | 0.332 | 0.039 | 0.000 | 0.000 |
| E. & S.-E. Europe | 0.356 | 0.620 | 0.079 | 0.969 | 0.861 | 0.175 | 0.290 | 0.042 | 0.025 | 0.106 |
| Oceania & Australia | 0.213 | 0.350 | 0.028 | 0.650 | 8.538 | 0.380 | 0.339 | 0.116 | 0.739 | 0.387 |
| World | 0.248 | 0.152 | 0.015 | 0.233 | 1.004 | 0.197 | 0.125 | 0.035 | 0.002 | 0.000 |

* Including grazing
Source: Krausmann et al., 2008a

## Population and urban area forecast

Our scenario work for 2050 uses only one population forecast; that is, the UN medium variant (UN, 2007). We are aware of the uncertainties of population forecasts, with the state-of-the-art being probabilistic techniques that give likelihoods rather than precise values (Lutz et al., 2001, Lutz et al., 2004). But given the limited resources available for this study, and its nature as a scoping study, we have kept the number of parameters that were varied in the scenarios to a minimum and decided against the inclusion of different population scenarios.

We also use only one forecast for the land taken up by urban areas and infrastructure. This land use class contains two distinct components: (a) Urban areas, including urban settlement, transportation infrastructures, commercial and industrial areas, parks, etc. and (b) rural infrastructure areas, including rural settlements, farm houses and other buildings, rural transportation infrastructures, etc. We calculated both components separately, as follows:

- We assumed that rural infrastructure areas are mostly driven by the need to transport agricultural inputs and produce and by the need to house agricultural population and machinery. We therefore calculated the area of rural infrastructure as a percentage of cropland area in each region in each scenario. The percentages were derived from prior work for the year 2000: We applied the ratio between cropland and rural infrastructure in the year 2000 (Erb et al., 2007) for the year 2050, so that rural infrastructure changes in parallel with total cropland area. In quantitative terms, rural infrastructure is much larger than urban areas.
- For urban areas, we assumed that the per-capita amount of urban area would stay constant from 2000 to 2050, i.e. urban area was scaled with the projected increase of urban populations from 2000 to 2050. For East and South-East Europe, the UN population projection predicts a shrinking urban population; in this region we kept the urban areas constant. We are aware that this simple projection is questionable, because urban area per capita might grow due to increasing affluence (which tends to reduce density of urban areas) or decline due to increased poverty in some regions. However, the scope of this study did not allow for a more sophisticated modelling approach.

As the results for rural infrastructure depend on the assumed development of cropland areas, these results will be discussed later on in this report.

Urban areas are kept constant in all scenarios, so these serve as a common framework condition for all scenarios and are reported below together with our assumptions on population growth in Table 6. Total population is forecast to grow from 2000 to 2050 by a factor of 1.51 from 6.05 billion to 9.16 billion. Urban population, in contrast, is assumed to grow by a factor of 2.24 from 2.84 billion to 6.37 billion. We assume that this growth in urban population results in a growth of urban areas from 279 180 km$^2$ to 532 880 km$^2$. This sounds large, but it is not so large when compared to existing and projected cropland areas (see below), so the possible error introduced by our crude calculation method might not be overly important.[4]

In our judgement this is a very conservative (i.e. low) estimate of the future growth of urban areas. The development of widespread urban sprawl may easily result in a much higher consumption of biologically highly valuable land for urban areas.

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[4] Of course, we would be glad to improve our scenarios by introducing a more sophisticated method. One possible method would be to work with spatially explicit population forecasts (Grübler et al., 2007), but at present their coarse resolution (0.5° grid) as well as resource constraints prevented such an approach.

**Table 6. Population in 2000 and 2050, growth of urban population and urban area until 2050**

| | Total population 2000[1] | Urban population 2000[2] | Total population 2050[3] | Urban population 2050[2] | Growth of urban population | Urban area 2000[4] | Urban area 2050[5] |
|---|---|---|---|---|---|---|---|
| | [million] | | | | [factor] | [1000 km$^2$] | |
| N. Africa & W. Asia | 359.1 | 192.5 | 598.0 | 454.8 | 2.36 | 16.60 | 39.22 |
| Sub-Saharan Africa | 643.4 | 222.6 | 1760.3 | 1064.4 | 4.78 | 17.96 | 85.86 |
| Central Asia, Russ. Fed. | 201.8 | 131.2 | 187.6 | 138.5 | 1.06 | 17.11 | 18.07 |
| E. Asia | 1481.1 | 589.7 | 1581.7 | 1169.7 | 1.98 | 7.95 | 15.77 |
| S. Asia | 1406.1 | 423.4 | 2455.7 | 1400.4 | 3.31 | 27.36 | 90.47 |
| S.-E. Asia | 516.3 | 202.7 | 761.6 | 556.6 | 2.75 | 6.95 | 19.09 |
| N. America | 315.8 | 249.7 | 445.2 | 401.4 | 1.61 | 86.56 | 139.13 |
| Latin America, Carribb. | 514.1 | 393.4 | 767.8 | 681.5 | 1.73 | 13.93 | 24.14 |
| W. Europe | 389.9 | 293.8 | 412.5 | 357.3 | 1.22 | 52.03 | 63.29 |
| E. & S.-E. Europe | 192.3 | 118.1 | 143.4 | 110.4 | 0.93 | 23.16 | 23.16 |
| Oceania & Australia | 30.4 | 21.5 | 47.7 | 36.4 | 1.69 | 9.56 | 16.20 |
| World | 6050.2 | 2838.6 | 9161.5 | 6371.4 | 2.24 | 279.18 | 532.88 |

[1] Source: FAO, 2005
[2] Source: UN, 2008
[3] Source: UN, 2007
[4] Source: Joint Research Center, 2002
[5] Source: Model result (urban area 2000 multiplied with growth of urban population; E. & S.-E. Europe kept constant).

## Cropland potentials

Assessing the amount and spatial distribution of land that would be suitable as cropland but is at present not used as such is a highly difficult task. Results of most assessments of additional cultivable land (e.g., Fischer and Heilig, 1997, IIASA and FAO, 2000) have been severely criticized (Young, 1998, Young, 1999). In general, most such assessments are based on a 'land balance' approach that basically proceeds by (1) identifying cultivable areas and (2) subtracting areas already cultivated. Practitioners have argued (Young, 1999, p. 11) that this approach suffers from the following problems: (1) Overestimation of cultivable land, for example due to failure to take inclusions of uncultivable land (hills, rock, outcrops, minor water bodies, etc.) into account. (2) Underestimation of land already cultivated. Young (1999) documents cases where cropland areas were underestimated by up to 50%, in particular in Sub-Saharan Africa. (3) Insufficient attention to land demand for other purposes than cultivation (e.g., grazing or settlements). As a result, Young (1999) suggests that estimates of the area of additional cultivable land should be reduced by around 50% in order to get realistic estimates.

Solving these problems remains a considerable scientific challenge that has yet to be solved satisfactorily. We have, however, taken some of these factors into account:

- We explicitly consider urban and infrastructure areas and their expected growth until 2050, as discussed above. We also consider rural infrastructure area required to support the cropland assumed to exist 2050, depending on the scenario assumptions. It should be noted, however, that our assumptions for urban areas are probably rather conservative (i.e. low).
- We explicitly consider land under forestry as well as currently unused land (wilderness, including unused forests). In areas where this unused land has some noteworthy

biological productivity (NPP), we assume that these are pristine areas that should not be cultivated due to their conservation value, i.e. we exclude them from land use in all scenarios.

- We do not assume deforestation in our scenarios. That is, we assume that growth in cropland and urban areas takes place on areas currently used as grazing lands. Because our land-use dataset is a closed budget model, assuming neither deforestation no use of wilderness areas implies that any expansion of urban and/or cropland areas reduces the area of grazing land. Because our model includes livestock feed balances that distinguish market feed (from cropland), non-market feed (fodder crops and crop residues from cropland, rough grazing from grazing areas), we are able to detect whether the remaining grazing land can support the required livestock feed energy demand or not.

We are aware that both assumptions (no use of wilderness/unused areas and no further deforestation) are not realistic and that currently agriculture is a key driver of deforestation. But this does not affect our ability to answer the main underlying questions: As our scenario calculations will show, the ability of the global agricultural system to provide enough food and fibre is constrained by cropland production, not by the production of forage on grazing areas. We explicitly consider two expansion scenarios for cropland, neither of which constrains the ability of the grazing land areas assumed to exist in 2050 to produce the amount of forage required. Our assessment of the scenarios – that is, the calculation which combinations of demand (diets) and supply technology (intensive, intermediate, organic and humane) are feasible – is therefore not affected by this assumption. We are aware that robustly enforced policy measures would be required to minimize future (tropical) deforestation and that deforestation will continue if such measures are not implemented. We here show that a whole range of options exist to feed the world even without deforestation. Note, however, that our results are only based on biophysical considerations; economic or other factors are likely to result in different outcomes, in particular in the absence of strong measures to prevent additional tropical deforestation.

Table 7 compares the area of current infrastructure and cropland with estimates of the extent of grazing areas from our grazing land quality assessment (Erb et al., 2007), an assessment of cropland suitability (Ramankutty et al., 2002) and assessments of cropland suitability from the Global Agro-Ecological Zones (GAEZ) maps (IIASA and FAO, 2000). Our assessment of grazing land quality was based on its NPP as well as on land cover information (e.g., bare areas or shrubland was assumed to be less suitable for grazing than areas with herbaceous vegetation). For details see Erb et al. (2007).

**Table 7. Comparison of current (2000) infrastructure and cropland areas with two assessments of cropland suitability and current grazing areas**

| | Erb et al. 2007 | | Ramankutty et al. 2002 | | GAEZ: Climate, soil, terrain and slope constraints combined (plate 28) | | | GAEZ: Suitability for rainfed cultivation – maximizing technology (plate 46) | | | | GAEZ: Suitability for rainfed cultivation, max. techn., without forest areas (plate 56) | | | | Erb et al. 2007 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Infra-struct. 2000 | Plus crop-land 2000 | Crop-land suita-bility >0.7 | Crop-land suita-bility >0.5 | No or (very) few con-straints | Plus partly with con-straints | Plus frequ. severe con-straints | Very high + high | Plus good | Plus me-dium | Plus mode-rate | Very high + high | Plus good | Plus me-dium | Plus mode-rate | Gra-zing class 1 | Plus grazing class 2 |
| | [million km$^2$] | | | | | | | | | | | | | | | | |
| N. Africa, W. Asia | 0.042 | 0.805 | 0.512 | **0.888** | 0.133 | 0.624 | **1.214** | 0.044 | 0.122 | 0.337 | 0.646 | 0.041 | 0.115 | 0.320 | 0.610 | 0.043 | 0.060 |
| Sub-Saharan Africa | 0.111 | 1.892 | 1.536 | **3.999** | 0.394 | **3.726** | **7.498** | **5.099** | **7.555** | **9.851** | **12.313** | **4.098** | **6.242** | **8.253** | **10.305** | 3.208 | 5.768 |
| Centr.Asia, Russ.Fed. | 0.189 | 1.761 | 1.645 | **2.967** | 0.317 | **2.082** | **3.143** | 1.149 | 1.761 | **2.496** | **3.192** | 0.784 | 1.218 | 1.676 | **2.174** | 0.864 | 1.534 |
| E. Asia | 0.140 | 1.744 | 2.286 | **3.922** | 0.224 | 1.223 | **2.671** | 0.690 | 1.026 | 1.417 | **1.989** | 0.659 | 0.961 | 1.300 | **1.788** | 0.989 | 1.446 |
| S. Asia | 0.113 | 2.419 | 1.047 | 2.292 | 0.382 | 1.169 | **2.391** | 1.475 | 1.911 | 2.269 | **2.595** | 1.445 | 1.862 | 2.195 | **2.485** | 0.327 | 0.460 |
| S.-E. Asia | 0.039 | 0.970 | 0.536 | **1.063** | 0.107 | 0.876 | **2.113** | 0.573 | 0.858 | **1.225** | **1.654** | 0.476 | 0.662 | 0.877 | **1.098** | 0.625 | 1.049 |
| N. America | 0.337 | 2.577 | 2.433 | **3.521** | 0.860 | **2.952** | **4.188** | 2.142 | **3.079** | **3.991** | **5.100** | 1.335 | 1.883 | 2.451 | **3.263** | 1.022 | 1.711 |
| Lat.America, Carribb. | 0.064 | 1.750 | 3.727 | **5.584** | 0.651 | **3.343** | **7.312** | **4.264** | **6.529** | **8.741** | **11.016** | **2.438** | **3.652** | **4.823** | **5.987** | 3.062 | 4.811 |
| W. Europe | 0.198 | 1.060 | 1.077 | **1.596** | 0.356 | 0.997 | **1.753** | 0.489 | 0.844 | **1.259** | **1.676** | 0.466 | 0.783 | **1.125** | **1.458** | 0.509 | 0.738 |
| E.&S.-E. Europe | 0.103 | 1.044 | 0.865 | **1.294** | 0.392 | **1.062** | **1.614** | 0.701 | **1.119** | **1.568** | **1.883** | 0.666 | **1.058** | **1.463** | **1.718** | 0.330 | 0.397 |
| Oceania, Australia | 0.023 | 0.563 | 0.520 | **1.302** | 0.092 | 0.507 | **1.486** | 0.288 | 0.546 | **1.026** | **1.671** | 0.250 | 0.450 | **0.832** | **1.353** | 0.434 | 0.796 |
| World | 1.360 | 16.585 | 16.182 | 28.429 | 3.906 | 18.560 | 35.382 | 16.914 | 25.351 | 34.181 | 43.735 | 12.657 | 18.886 | 25.312 | 32.238 | 11.413 | 18.770 |

Bold numbers indicate land potentials, i.e. in regions in which more land of a certain class is available than was used for cropland and infrastructure in 2000.

Infrastructure and cropland already covered 16.6 million km$^2$ in 2000. Globally, the area with an estimated cropland suitability index >0.7 according to Ramankutty et al., 2002 is almost equal, but with considerable regional differences. The cropland suitability index used by Ramankutty et al. (2002) is calculated using climate indicators (growing degree days and an indicator of water availability) and soil indicators (basically soil pH and carbon) to estimate the probability of a grid cell to possess physical characteristics that allow rainfed cultivation. In some regions, cropland and infrastructure area is already larger than this highly suitable land which indicates a scarcity of land highly suitable for cultivation. In such regions, cropland expansion will probably face considerable challenges and is likely to require expensive investments, e.g. in irrigation technologies or other measures of land improvement. In other regions, considerable areas with a cropland suitability index >0.7 are not yet used as cropland or infrastructure – in these regions, cropland expansion can be assumed to be easier and less costly. Globally, only about 57% of the land with a cropland suitability index >0.5 is already used for infrastructure and cropland. There is, however, one region where even worse land seems to be used, i.e. South Asia, where cropland and infrastructure areas exceed the area with a cropland suitability index >0.5 by 6 %.

The GAEZ assessment of climate, soil, terrain and slope constraints suggests that the global area of land with no, very few and few constraints is far smaller than the area already used for cropland plus infrastructure. If we add the land classified as ‘partly with constraints’, we get a global sum slightly higher than the area of land already used for cropland and infrastructure. Again, we find regions where this suitability class is not sufficient to host all current cropland and infrastructure. Cropland expansion potentials seem to prevail in some regions, most notably in Sub-Saharan Africa and Latin America and the Caribbean. Only if we include the class defined as ‘land with frequent and severe constraints’ do we find cropland expansion potentials in all regions.

The GAEZ also provides suitability estimates for rainfed agriculture with improved technology that distinguish between potentials on currently forested land and potentials restricted to non-forested land. Here we feel that the assessment that excludes forests is most interesting (plate 56). It suggests that spare land with very high and high suitability for cultivation only exists in Sub-Saharan Africa and Latin America and the Caribbean. If we also include ‘good’ land, then some area becomes available also in East- and South-East Europe. Other regions only seem to have land potentials when we also include land of medium suitability (Western Europe, Oceania and Australia).

Note, however, that the question of how well-suited this land is for large-scale, intensive cultivation is highly contested and uncertain. Assessments such as those by Ramankutty et al. (2002) and the GAEZ are based on scarce data that were extrapolated for large areas. In-depth regional studies suggest that one should be very cautious not to overestimate the cropland expansion potential of regions such as Sub-Saharan Africa, where the transfer of European cultivation techniques has caused large-scale soil erosion and European agricultural expertise seems to have failed, at least in the past (e.g., Showers, 2006). Moreover, much of the cultivable land in Sub-Saharan Africa and South America is under valuable forests or in protected areas. Tropical soils could potentially lose fertility rapidly if taken into cultivation and are highly vulnerable to climate-change impacts (Ramankutty et al., 2002). It is estimated that only 7% of the cultivable areas in Sub-Saharan Africa and only 12% of those in Latin America and the Caribbean are free from severe soil constraints that limit sustainable and profitable production (IAASTD, 2009, p. 150).

A comparison with our estimate of the area under grazing classes 1 and 2 (see the last two columns of Table 7) shows that regions with much land in the grazing land class 1 (best-suited grazing area) are also those in which large potentials for cropland expansion are found by both Ramankutty and the GAEZ, whereas those regions with little cropland expansion potential also have small areas of high-quality grazing land.

We have therefore adopted the following modelling strategy: if growth of urban areas and growth of demand for cropland products results in a need for more cropland, we assume that cropland expands into grazing land of the highest quality (class 1). Of course, this then results in a reduction of the availability of roughage which we consider in our livestock feed balances and which affects the livestock production system in the respective region(s). The assumptions used to determine cropland areas in each region in our scenario runs are explained in the next chapters.

## World agriculture towards 2030/2050: An agricultural intensification scenario

We used the FAO reports ‘World agriculture: towards 2015/2030 – an FAO perspective’ (Bruinsma, 2003) and ‘World agriculture towards 2030/2050’ (FAO, 2006b) as a baseline. These reports are the most authoritative sources for forecasts on development of crop production, yields and area expansions available today. The latter is an interim report that extends the 2015/2030 forecasts until 2050 based on annual growth rate projections for crop production for selected important food crops (cereals, oil crops, and sugar), with regional resolution for developing countries. Industrial countries are not disaggregated. In contrast, the FAO report for 2015/2030 gives information on annual growth rates of production for major crop groups (including roots and tubers, coffee, cocoa, bananas and rubber) until 2030. Furthermore, this report gives 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[5] to the increases of overall production. The report also explicitly reports on forecasts for the area and yields of the major crops for five regional groups of developing countries. This implies that the FAO reports, while indicating changes in crop production and land use by forecasting relative changes for the most important crops until 2050, are in themselves not sufficient to derive a consistent set of data on the projected areas and crop production volumes for the year 2050 as required for our biomass balance model.

We therefore combined the data given in these reports with a database containing data on the country level on production, area harvested, and yields for the major crop groups,[6] the extent of arable land including fallows, for the period 1960 to 2000 in decadal steps (see Krausmann et al., 2008a for a description of the database for the year 2000). In a first step, all data were converted to dry matter units using standard conversion tables (Krausmann et al., 2008a). From the combination of historic time series data with the relative information on growth rates and other important parameters, together with own assumptions to close data gaps not reported in the FAO studies, we constructed a consistent database containing information on harvested area, yields per unit area and year and total production for 2050 for each of the 7 major crop groups used in the study (cereals, oil bearing crops, sugar crops, pulses, roots and

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[5] 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.

[6] For a definition of crop aggregates see the section ‘Definition of study regions and crop aggregates. For a description of the biomass flow and land use data see section ‘Global land use and biomass flow data for the year 2000’.

tubers, vegetables and fruits, and other crops, including fibres, coffee, etc.), and estimates on the cropping intensity in 2050. Figure 2 and Figure 3 display the development of overall cropland production, yields, cropping intensity, and cropland area from 1960 until 2050 for the eleven world regions and for the major crop groups.[7] These data are available separately and consistently for all seven crop groups.

One intricacy involved in such calculations is associated with the concept of yield. The concept of ‘harvest yield’ refers to the amount of product gained per unit of area that is actually harvested and per harvest event. Its meaning differs from the concept of ‘land-use yield’ which refers to the amount of product harvested per unit area designated for a defined crop and per year. The difference is that areas may be harvested more than once per year (multicropping) or may lie fallow. In calculating the harvest yield, only areas actually harvested are taken into account. If they are harvested twice per year, the area is also counted twice. In calculating the land-use yield, area is counted only once, regardless of the number of harvests achieved per year. If the land remains fallow, its area is nevertheless taken into account when calculating the land-use yield, but not when calculating the harvest yield. In our top-down modelling strategy, working with land-use yields is much easier because the tons of product (t DM/yr) can be calculated by multiplying the area of land (ha) devoted to a defined crop aggregate by yield (t DM/ha/yr). If one would work with harvest yields, cropping intensity[8] has to be modelled explicitly. As no good data were available to do that, we decided to work with land-use yields.

The FAO does not report projections for fodder crop production up to 2050. In order to fill this gap, 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 results of this assessment, in particular the outcomes on crop yield development, were cross-checked for plausibility with current crop yields at the national scale (e.g. FAOstat), alternative data on yield developments (Rosegrant et al., 2001), and corrected for maximum achievable yields for individual cultivars (Fischer et al., 2000) where necessary (e.g. for oil crops and sugar, where the analysis based on FAO information yielded implausibly high yields for 2050 in certain regions). These cross-checks resulted in a slight deviation of the result of this assessment from the FAO projections up to 2050, which nevertheless was neglected as these deviations were small compared to the other uncertainties involved in such a long-term projection, including the uncertainties resulting from the lack of consistent and comprehensive information.

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[7] Note that the modelling step 2030 is a result of the modelling procedure and is not further used in the assessment.

[8] Defined as the number of harvests per year: >1 in the case of multicropping, <1 in the case of fallow.

**Figure 2. Cropland production scenario 2050. Development of production (a), harvest yields (b-left), cropping intensity (b-right) and arable land area (c) 1960 – 2050 of food crops, break-down to world regions. Source: see text.**

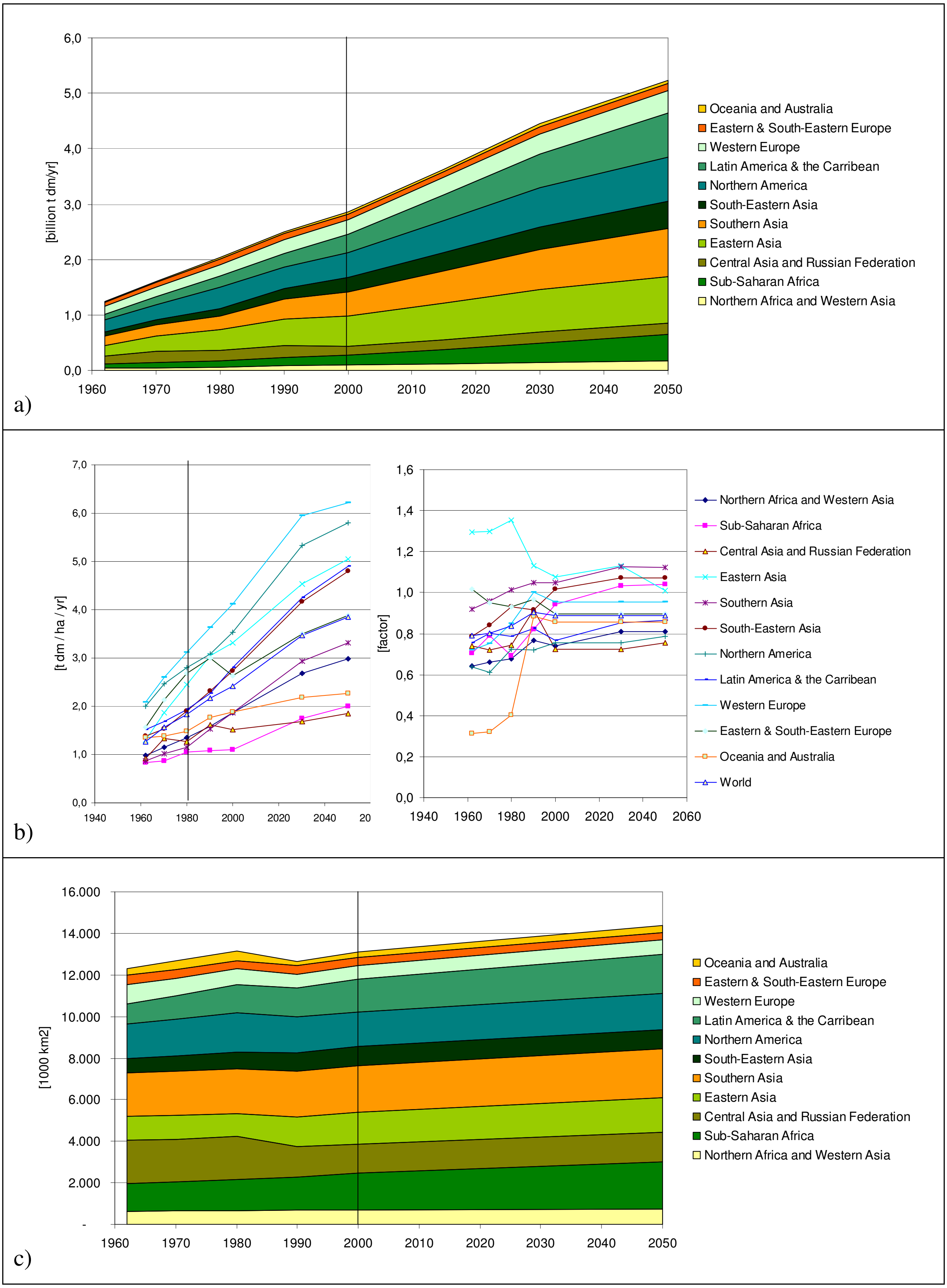
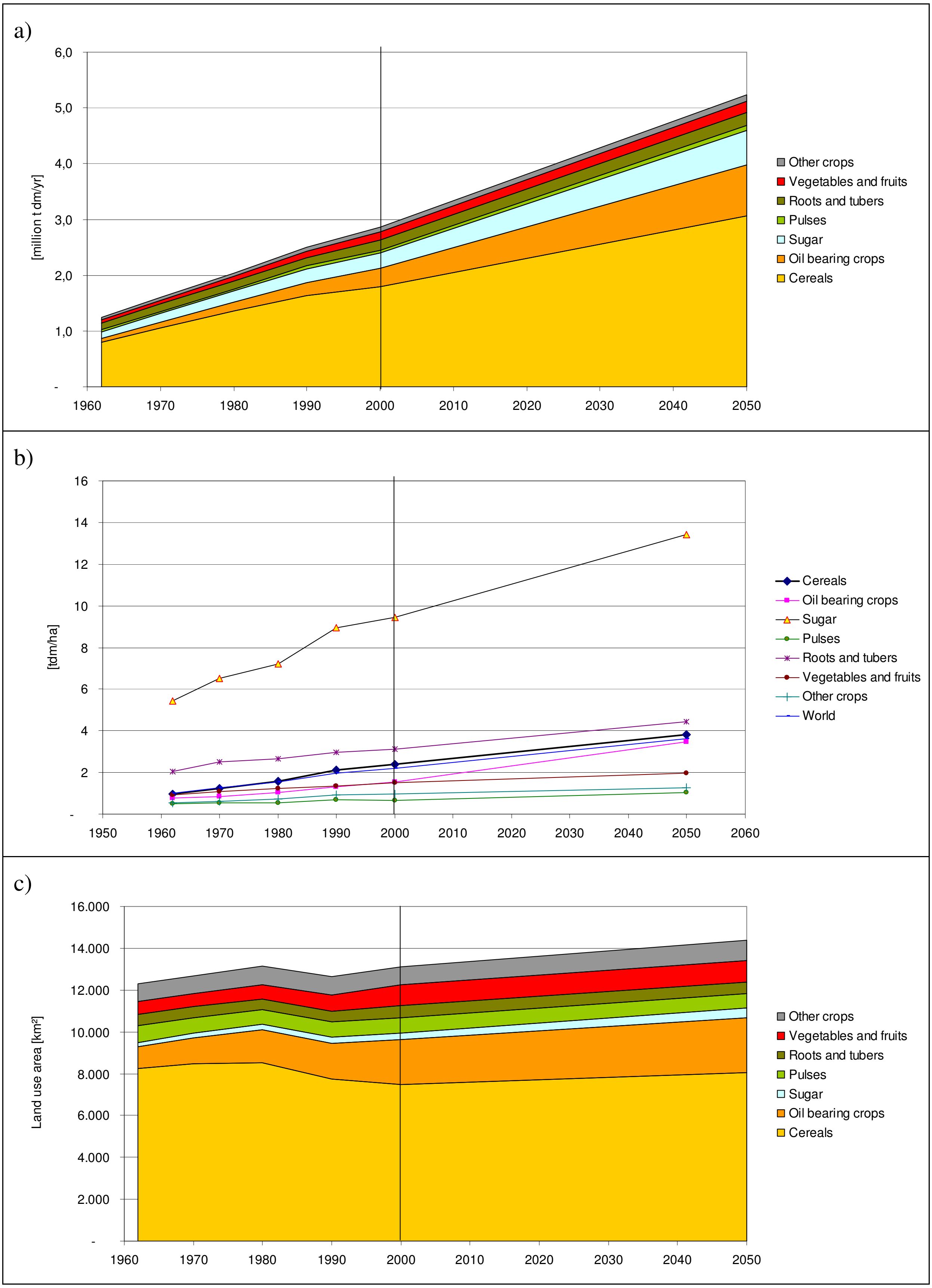


**Figure 3. Cropland production scenario 2050. Development of (a) production, (b) land use yields (harvest yield times cropping intensity) and (c) arable land area 1961 – 2050 of food crops, break-down to major crop groups. For sources and details, see text.**



The scenario elaborated by the FAO describes a world in which agricultural intensification progresses rapidly and yields are forecast to reach astonishing levels for some crops and regions (see Figure 2 and Figure 3): Overall production on cropland increases by 68% (dry matter), with a maximum increase of +154% and +121% for Sub-Saharan Africa and Latin America, respectively, and results in a total production of 6.0 Gt DM/yr (1 Gigaton = 1 Gt = $10^9$ t = 1 billion tons) in 2050. This is mainly due to land-use yield developments (i.e. the combined effect of harvest yields and changes in cropping intensity), which increases by 54% on average of the total cropland, with maximum growth for oil crop yields, which increase by a factor of 2.2 in the world average. In particular, in Western Europe and North America, cropland yields reach particularly high levels.

It is difficult to judge whether these impressive yield gains will be realized. Biologists argue that many options to achieve yield gains have already been discovered and are approaching physiological limits. For example, further improvements of harvest indices that seek to increase the share of the desired product (e.g. grain) at the expense of supporting tissues such as leaves and stems (straw) seem unlikely for many cultivars because of physiological limits. Harvest indices of the most advanced rice cultivars are already around 0.50-0.55 and it seems unlikely that this can be increased substantially (Cassman, 1999; Peng et al., 2000). 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 East Asia) or yields have even become stagnant (e.g., rice in Japan, Korea, China) as they approach limits set by soil and climate (Tilman et al., 2002). Soil degradation and depletion of nutrient stocks in soils is seen as an additional challenge (Cassman, 1999). 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 indispensible for maintaining growth in crop yields (Kahn et al., 2009) and economic constraints may further prevent the realization of technical yield potentials (Koning and van Ittersum, 2009) Climate change will add even more challenges, as analyzed explicitly in this study (see below).

**Table 8. Cropland areas and changes in 2000 and 2050, according to our recalculation of the FAO scenario 'World agriculture towards 2030/50' (FAO) and assumption used in the 'massive change scenario'.**

| | Cropland 2000 | Cropland 2050 FAO / BAU | | Cropland 2050 massive change | |
|---|---|---|---|---|---|
| | [1000 km²] | [1000 km²] | [change] | [1000 km²] | [change] |
| Northern Africa and Western Asia | 763 | 819 | +7.2% | 874 | +14.5% |
| Sub-Saharan Africa | 1 781 | 2 283 | +28.2% | 2 785 | +56.3% |
| Central Asia and Russian Federation | 1 572 | 1 635 | +4.0% | 1 699 | +8.1% |
| Eastern Asia | 1 604 | 1 694 | +5.7% | 1 785 | +11.3% |
| Southern Asia | 2 305 | 2 428 | +5.3% | 2 550 | +10.6% |
| South-Eastern Asia | 931 | 930 | -0.1% | 931 | 0.0% |
| Northern America | 2 240 | 2 335 | +4.3% | 2 430 | +8.5% |
| Latin America & the Carribbean | 1 685 | 2 037 | +20.9% | 2 388 | +41.7% |
| Western Europe | 862 | 880 | +2.1% | 899 | +4.2% |
| Eastern & South-Eastern Europe | 941 | 890 | -5.4% | 941 | 0.0% |
| Oceania and Australia | 540 | 696 | +28.8% | 851 | +57.7% |
| World | 15 225 | 16 627 | +9.2% | 18 134 | +19.1% |

As shown in Table 8, cropland area increases at a much slower rate than yields. Globally, cropland is forecast to be 9% larger in 2050 than in 2000, reaching 16.6 million km². This estimate is well in line with results of other studies. For example, IIASA scenarios suggest that global cropland area will grow by +6% in scenario B1, +9% in Scenario B2 and +12% in scenario A1 (http://www.iiasa.ac.at/Research/GGI/).[9] Most global agricultural scenarios assume that growth in agricultural production will depend mostly on increases of yields and only to a smaller extent on a growth of cropland areas (Tilman et al., 2001, IAASTD, 2009).

Table 8 shows that, well in line with the cropland potential studies discussed in Table 7, cropland expansion in the FAO projection is expected to be largest in Sub-Saharan Africa and Latin America & the Carribbean and Oceania/Australia. This is no surprise as these projections are heavily influenced by the GAEZ.

In our modelling, we have adopted two scenarios for cropland expansion. The first follows the FAO projection, in line with the GAEZ. In the second scenario, we assumed that cropland expansion will be double that of the FAO projection (see Table 8). In regions where cropland is assumed to contract in the FAO projection, we keep cropland areas constant. The rationale behind this assumption was that we wanted to analyze the impact of an expansion of cropland that is much larger than that assumed in most other scenario analyses. We assume that this cropland expansion takes place on current grazing areas. Reduced production on grazing areas is taken into account in our livestock feed balances as explained below.

Table 9 summarizes the total land use budged for the two scenarios. Only infrastructure area, cropland and grazing land are assumed to be subject to change, all other land use types are supposed to remain unchanged. Table 9 also shows the changes of infrastructure area as the sum of urban infrastructure areas (see above) and rural infrastructure areas. The latter is modelled as a fraction of cropland, applying the ratio between rural infrastructure area and cropland in the year 2000 and is therefore different in the two scenarios.

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[9] A1, B1 and B2 are scenarios from the IPCC work on future greenhouse gas emissions. The definition of these scenarios is explained in Footnote 11.

**Table 9. Land use in 2050 in the 11 study regions according to the two land use scenarios**

| **FAO/BAU 2050** | Infrastructure | | Cropland | | Forestry | | Grazing land | | Unused and Non-productive land | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | [mio. km²] | [% ] | [mio. km²] | [% ] | [mio. km²] | [% ] | [mio. km²] | [% ] | [mio. km²] | [% ] | [mio. km²] | [% ] |
| N. Africa and W. Asia | 66 | 159% | 819 | 107% | 268 | 100% | 1 658 | 95% | 7 468 | 100% | 10 283 | 100% |
| Sub-Saharan Africa | 205 | 185% | 2 283 | 128% | 5 828 | 100% | 11 271 | 95% | 4 388 | 100% | 23 980 | 100% |
| Central Asia and Russian Fed. | 197 | 104% | 1 635 | 104% | 7 155 | 100% | 6 670 | 99% | 4 774 | 100% | 20 436 | 100% |
| E. Asia | 156 | 111% | 1 694 | 106% | 2 121 | 100% | 5 040 | 98% | 2 522 | 100% | 11 537 | 100% |
| S. Asia | 181 | 160% | 2 428 | 105% | 850 | 100% | 2 364 | 93% | 848 | 100% | 6 675 | 100% |
| S.-E. Asia | 51 | 131% | 930 | 100% | 2 098 | 100% | 1 320 | 99% | 84 | 100% | 4 488 | 100% |
| N. America | 400 | 119% | 2 335 | 104% | 4 741 | 100% | 4 315 | 96% | 6 718 | 100% | 18 513 | 100% |
| Latin America and the Caribbean | 85 | 132% | 2 037 | 121% | 8 733 | 100% | 7 560 | 95% | 1 880 | 100% | 20 299 | 100% |
| W. Europe | 213 | 107% | 880 | 102% | 1 318 | 100% | 1 097 | 97% | 147 | 100% | 3 659 | 100% |
| E. and S.-E. Europe | 103 | 100% | 890 | 95% | 630 | 100% | 534 | 111% | 2 | 100% | 2 162 | 100% |
| Oceania and Australia | 34 | 146% | 696 | 129% | 1 216 | 100% | 3 318 | 95% | 3 121 | 100% | 8 390 | 100% |
| **World** | **1 690** | **124%** | **16 627** | **109%** | **34 958** | **100%** | **45 148** | **96%** | **31 951** | **100%** | **130 379** | **100%** |
| | | | | | | | | | | | | |
| **Massive LU Change 2050** | | | | | | | | | | | | |
| N. Africa and W. Asia | 68 | 163% | 874 | 114% | 268 | 100% | 1 601 | 92% | 7 468 | 100% | 10 283 | 100% |
| Sub-Saharan Africa | 231 | 208% | 2 785 | 156% | 5 828 | 100% | 10 743 | 91% | 4 388 | 100% | 23 981 | 100% |
| Central Asia and Russian Fed. | 204 | 108% | 1 699 | 108% | 7 155 | 100% | 6 600 | 98% | 4 774 | 100% | 20 436 | 100% |
| E. Asia | 163 | 116% | 1 785 | 111% | 2 121 | 100% | 4 942 | 96% | 2 522 | 100% | 11 537 | 100% |
| S. Asia | 185 | 164% | 2 550 | 111% | 850 | 100% | 2 237 | 88% | 848 | 100% | 6 675 | 100% |
| S.-E. Asia | 51 | 131% | 931 | 100% | 2 098 | 100% | 1 319 | 99% | 84 | 100% | 4 488 | 100% |
| N. America | 411 | 122% | 2 430 | 109% | 4 741 | 100% | 4 209 | 94% | 6 718 | 100% | 18 513 | 100% |
| Latin America and the Caribbean | 96 | 149% | 2 388 | 142% | 8 733 | 100% | 7 198 | 91% | 1 880 | 100% | 20 300 | 100% |
| W. Europe | 216 | 109% | 899 | 104% | 1 318 | 100% | 1 076 | 95% | 147 | 100% | 3 659 | 100% |
| E. and S.-E. Europe | 103 | 100% | 941 | 100% | 630 | 100% | 482 | 100% | 2 | 100% | 2 162 | 100% |
| Oceania and Australia | 38 | 163% | 851 | 158% | 1 216 | 100% | 3 159 | 91% | 3 121 | 100% | 8 390 | 100% |
| **World** | **1 765** | **130%** | **18 134** | **119%** | **34 958** | **100%** | **43 566** | **93%** | **31 951** | **100%** | **130 379** | **100%** |

[%] indicates percent of extent in 2050 compared to the land use extents in 2000

## Yields in organic cropping systems

Although the roots of organic agriculture are much older, certified organic agriculture as we know it today began with the foundation of the International Federation of Organic Agriculture Movements (IFOAM) during an organic agriculture congress in Versailles (France) in 1972 (Kirchmann et al., 2008). Since then, this organization has promoted the adoption of organic agriculture and set up standards and certification schemes.

The general principles of organic agriculture set up by IFOAM are (1) sustaining and enhancing health of the soil, plants, animals and humans, (2) the use, emulation and sustenance of ecological systems and cycles, (3) ensuring fair relationships between people, generations and between human and animals, and (4) the care for the environment. These general principles translated into specific standards, at the core of which are the exclusion of pesticides and synthetic fertilizers in crop production, as well as standards for the humane keeping of animals, including restrictions on their feed.

Since then, many studies have demonstrated that organic agriculture is beneficial for the structure and organic matter in soils (Mäder et al., 2002, Marriott and Wander, 2006, Fließbach et al., 2007), reduces soil erosion (Reganold et al., 1987, Siegrist et al., 1998), is more biodiversity-friendly than intensive agriculture (Bengtsson et al., 2005, Hole et al., 2005) and tends to result in lower GHG emissions, in particular due to the lack of use of synthetic N fertilizers prevalent in intensive agriculture. The question remains, however, whether a shift from intensive to organic agriculture might reduce food security or lead to poorer diets. Some critics have argued that due to its lower productivity, organic agriculture could not feed a future world population of 9 or 10 billion people (Adams, 1990, Connor, 2008).

There is no conclusive answer to the crucial question on the relative productivities of organic and intensive conventional ('industrialised') agriculture. While some claim that a large-scale conversion from intensive to organic agriculture would decrease yields only slightly, or might even allow for yields increases in some regions (Pretty et al., 2003, Halweil, 2006, Badgley et al., 2007), others claim that high-yielding agriculture is only possible if based on massive inputs of synthetic fertilizers. Thus, they propose that a conversion to organic agriculture would severely reduce yields (e.g., Borlaug, 1994, Connor, 2008, Trewavas, 2001).

One reason for this ongoing debate is the difficulty involved in comparing yields of organic and industrialised agriculture. The claims that organic agriculture could maintain yields comparable to industrialised agriculture are based on the crop yield per harvest event, for example the wheat or maize yield achieved per hectare and year of a harvested wheat or maize field. While industrialised agriculture can maintain high yields of maize, wheat and other highly valuable crops through inputs of inorganic fertilizer with limited crop rotation, organic agriculture has to rely on complex crop rotation schemes in which leguminous crops are used to fix atmospheric nitrogen in order to maintain soil fertility, thereby replacing N inputs from synthetic fertilizers. One could say that in organic agriculture, the leguminous crops that are ploughed into the soil are playing the role of the fertilizer factory. This additional area has to be considered in yield comparisons. Comparisons of yields of wheat or maize per harvest event are not sufficient because organic agriculture needs additional area for crops that are ploughed into the soil to replenish lost nutrients – and this area has to be added when comparing yields at a system level.

So how does organic agriculture perform when we do not only consider yields per harvest event, but also yields over the whole crop rotation cycle, i.e. with integration of leguminous crops? Concerning the yield per harvest event, experimental comparison of organic and industrialised agriculture suggest that crop yields per harvest event are on average a bit, but not much lower in organic than in industrialised agriculture. A collection of 272 comparative datasets, mainly from Europe and North America, found that organic yields (t/ha/yr) were on average approximately 20% lower than their industrialised counterparts (De Ponti and Pinstrup-Andersen, 2005, Halberg, 2006). Other meta-analyses concluded that organic yields amounted to 91-92% of the yields of industrialised systems (Badgley et al., 2007, Stanhill, 1990). The case studies summarized in Table A 8 in the Annex are in the same range, showing yields at between 71% and 103% of those in industrialised production. Another possibility to compare organic and industrialised yields is to look at administrative statistics. They show that in Europe, organic cereal yields are typically at a level of 60-70% of those under conventional management (Mäder et al., 2002, Fairlie, 2007). Thus, it is reasonable to assume that a shift from industrialised to organic management results in a yield decrease of about 10-30% per harvest event – a conclusion also drawn in IAASTD (2009).

As already mentioned, crop rotation is crucial to organic agriculture and therefore has to be considered as a further constraint on yields in organic agriculture. Typically, an organic arable farm has to devote 25-30% of its rotation to leguminous crops (von Fragstein und Niemsdorff and Kristiansen, 2006). The consideration of both yield-reducing factors, a 10-30% reduction of the yield per harvest event and the necessity to devote 25-30% of the cropland area to leguminous crops, leads to the conclusion that on a given area, organic agriculture can produce about 50-70% of the food produced by industrialised agriculture on the same area. A better integration of animals (growth of forage legumes and application of animal manure), as practiced routinely in organic systems, is likely to improve this ratio.

The case studies compiled in Table A 8 exemplify this relationship. Organic crop yields per harvest event are at between 71-103% of according industrialised crop yields per harvest event. However, this is only possible because they include either leguminous crops in their rotation and/or because of the input of organic fertilizers such as large amounts of poultry manure (e.g., Clark et al., 1998). In order to arrive at a more appropriate comparison concerning land use efficiency, the crop yield is reduced by the share of land that has to be spared for the cultivation of leguminous crops and/or animal feed in column 5 of Table A 8. It shows that considering this factor, yields in organic agriculture are approximately 40% lower than those of industrialised agriculture.

It is important to note that this crop yield decrease of about 40% only holds for the comparison between industrialised agriculture, with a harvest in each growing season and the intensive use of synthetic fertilizers and pesticides, and its organic counterpart. Such a land use management is applied in regions such as Europe and China that are, compared to their natural resource base, relatively densely populated. In other regions (e.g. some parts of New Zealand), industrialised agriculture is also based on crop rotation schemes that include leguminous crops, fodder crops or fallows. In this case, a shift from industrialised to organic agriculture does not require additional land for leguminous crops (e.g. Nguyen and Haynes, 1995). Yield reductions resulting from a conversion of industrialised to organic production can therefore be expected to be much lower in such regions. A decrease of about 30% might be a reasonable estimate in these regions. The study of Mäder et al. (2002), shown in Table A 8, exemplifies such a case.

All these arguments are only valid for industrialised systems. Developing regions with farming systems that have little or no access to synthetic fertilizers or pesticides are fundamentally different. In low-income tropical regions in particular, many farmers are confronted with severe problems such as decreasing soil fertility and degradation of soils due to decreasing fallow lengths and soil erosion, acid and phosphorus deficient soils (Bunch, 1999, Sanchez et al., 2000), or sandy soils showing a low capacity to hold nutrients (Diop, 1999). In many of these cases, agro-ecological measures such as the introduction of improved fallows and green manure or cover crops, the cultivation of ‘phosphorus accumulators’ (Bunch, 1999), the use of compost or dung and the better integration of livestock (Diop, 1999), or a rotation including leguminous fallows (e.g. Rao et al., 1998, Sanchez et al., 2000) can greatly improve yields.

One such example showing that an increase of food production in food-deficient regions has been described for the Ethiopian region of Tigray (Edwards et al., 2007). By increasing the use of compost, which was promoted by the regional government, the grain yield of the region doubled between 2003 and 2006 from 714 to 1,354 thousand tonnes, whereas the use of chemical fertilizers decreased during the same time.

Thus, the potential to increase food productivity by organic methods alone depends largely on present levels of productivity. A rough guide is that the lower the present yields compared to the potential yields in a region, the higher the possibility to improve yields with organic methods (Kotschi, 2009). As it is not known whether the mentioned case studies, as well as those presented in Table A 9, are representative for a region, it is difficult to assess the overall potential of organic agriculture in developing regions.

Note that organic yields, as used in our global calculations discussed below, are not necessarily a result of cultivation techniques that strictly adhere to standards such as those defined by the IFOAM. Given the difficulties in defining the impact of a general adoption of organic techniques on cropland yields over larger areas, we believe that our yield assumptions can serve as a proxy for agricultural systems that are based on lower inputs of agrochemicals and adopt environmentally less harmful techniques at the expense of output levels. To what extent environmental pressures can be reduced without such a large reduction of yields remains to be seen and will also depend on agricultural research and development. The IAASTD (2009) provides a lot of material that might be helpful in that respect.

### *Operationalisation for the scenario analysis*

The regional organic yield levels in the year 2050 were modelled by combining assumptions on the regional mix between high input (e.g. industrial) and low input (e.g. subsistence production) agriculture with the assumption that organic yields are 40% lower than the yields of industrialised, high-input systems, and identical in low input systems. We propose that this is a conservative set of assumptions. This results in different assumptions on the overall yield reduction for each region, and thus in different yield developments between 2000 and 2050 (see Figure 4a and 4b), because yields grow in regions with currently low yields but stay constant or even decline in regions with currently high yields in the ‘organic’ scenario.

As mentioned above, the ‘FAO intensive’ crop yield scenario shown in Fig. 4a represents a scenario of large-scale intensification of crop agriculture, with massive yield increases in particular for industrialised regions with already high yield levels in the year 2000. In order to be able to depict future pathways with less radical intensification, assuming that these steep increases in yields might not be achieved or even desirable if their potential negative environmental impacts can not be mitigated, we assumed a third crop yield development scenario (‘intermediate yields’), derived by building the arithmetic mean between ‘FAO intensive’ and ‘organic’ crop yields for 2050. Figure 4c displays the development of the ‘intermediate’ agricultural yields between 1962 and 2050 at the world region level as used in this study.

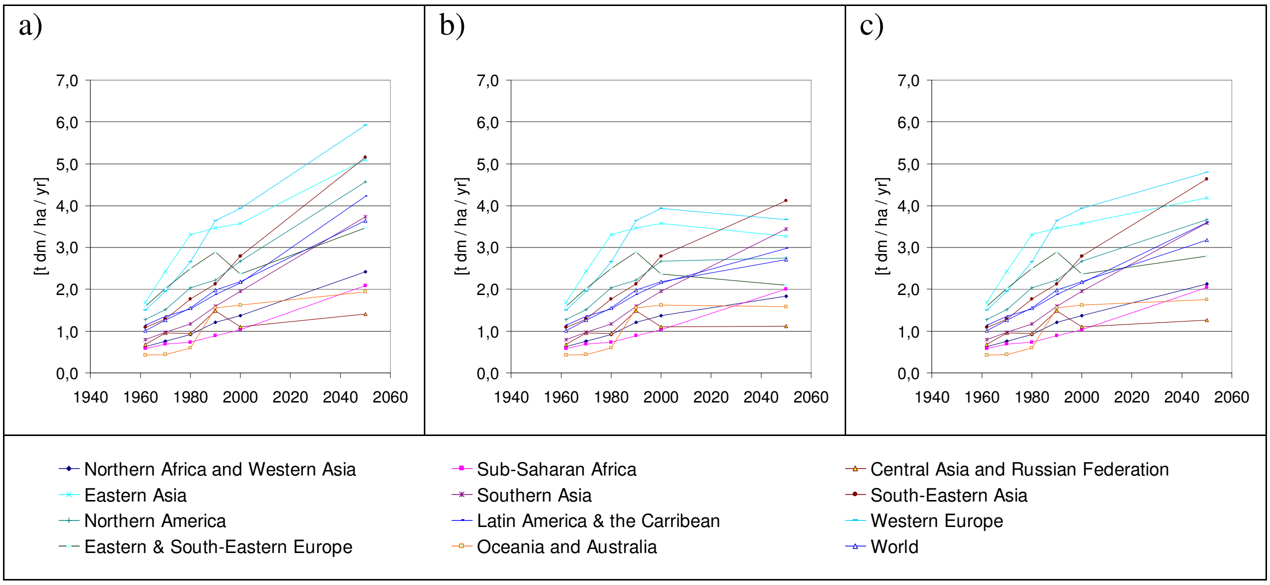

**Figure 4. Agricultural yields development 1960 - 2050. a) FAO intensive yields (see Figure 2), b) organic yields; c) intermediate yields. For details, see text.**

Such an ‘intermediate’ scenario may be interpreted as a situation in which half of the area is managed with organic techniques and the other half with intensive high-yield systems. Another interpretation would be that this is a trajectory in which ‘FAO intensive’ crop yield expectations cannot be met for economic (lack of investment) or biophysical (physiological limits, soil degradation, etc.) reasons. It can also be seen as a trajectory in which agro-ecosystems are not pushed to their very limits and some technical possibilities to push yields are foregone due to environmental considerations – so less intensive systems are used across the board.

## Taking climate-change impacts into account – possible orders of magnitude

The LPJmL computational model (Bondeau et al., 2007) was used to estimate the effects of changes in temperature, precipitation and $CO_2$ fertilization on yields of major crops globally at a spatial resolution of 0.5°x0.5°.[10] Yield simulations are based on process-based simulations of plant growth with LPJmL, a dynamic global vegetation model (DGVM) that includes not only ‘plant functional types’ (PFTs) to represent natural vegetation, but also ‘crop functional types’ to represent agricultural crops in a mechanistic coupled plant growth and water-balance model (for reference see Cramer et al., 2001, Lucht et al., 2002, Sitch et al., 2003, Gerten et al., 2004, Bondeau et al., 2007).

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[10] Changes in temperature and precipitation affect plant growth (NPP) in complex ways. Increases in temperature promote plant growth in many colder environments but may also reduce plant growth, in particular if precipitation declines or remains constant. Growth in precipitation mostly promotes plant growth except in environments that are already very wet, while a reduction in water availability almost always has a negative effect on plant growth. The level of atmospheric $CO_2$ affects NPP because plants need $CO_2$ for photosynthesis. The $CO_2$ concentration in the atmosphere can constrain photosynthesis under certain circumstances and increases in atmospheric $CO_2$ can alleviate these constraints. Moreover, increases in atmospheric $CO_2$ concentration reduce the amount of water plants lose through their stomata per unit of $CO_2$ absorbed, i.e. they affect water use efficiency which may have a significant impact on NPP in water-constrained (dry) environments.

We calculated percentage changes in agricultural productivity between two 10-year periods: 1996-2005 and 2046-2055, representing the average productivity of the years 2000 and 2050. Management intensity was calibrated to match national yield levels as reported by FAO statistics for the 1990s (Fader et al., 2009). National and regional agricultural productivities were based on calorie- and area-weighted mean crop productivity of wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed. Changes in management, breeding and cropping area are considered in other parts of this report; this section is only concerned with estimating the possible magnitude of the climate-change effect on agricultural yields. As we do not have an integrated model, we were not able to consider feedbacks between climate change, $CO_2$ fertilization and management; we here only estimate the possible impact of climate change, assuming constant management intensities as of the year 2000.

We assumed three different emission scenarios from the Special Report on Emission Scenarios (SRES): A1b, A2, B1 (Nakicenovic and Swart, 2000).[11] Each emission scenario was implemented in five different general circulation models (GCMs).[12] Climate data for these GCM-projections were generated by downscaling the change rates of monthly mean temperatures and monthly precipitation to 0.5° resolution by bi-linear interpolation and superimposing these monthly climate anomalies (absolute for temperature, relative for precipitation and cloudiness) on the 1961–1990 average of the observed climate (New et al., 2000, Österle and Gerstengarbe, 2003). Since there was no information about the number of wet days in the future, these were kept constant after 2003 at the 30-year average of 1971–2000.

Considerable uncertainty exists how $CO_2$ fertilization might influence future crop yields. This is due to both modelling uncertainties and due to the fact that it seems likely that there are indeed interrelations between management (e.g., nutrient and water availability) and the $CO_2$ fertilization effect. For example, if water or nutrient levels are insufficient to support additional plant growth, additional $CO_2$ cannot be expected to result in higher yields. To assess the range of $CO_2$ fertilization uncertainty (Long et al., 2006, Tubiello et al., 2007), each of the 15 scenarios was calculated twice: first, taking into account full $CO_2$ fertilization effects according to the prescribed SRES atmospheric $CO_2$ concentrations, and second, keeping atmospheric $CO_2$ concentrations constant at 370 ppm after 2000. In the latter case, yield changes are only driven by the modelled changes in precipitation and temperature (and the limited adaptation of management as described below), whereas in the latter case the full effect of changes in temperature, precipitation and $CO_2$ levels is taken into account. Production area was static at the prescribed year-2000 pattern. Relative management levels were calibrated to match observed current production levels, but sowing dates were assumed to be adapted to climate change as described by Bondeau et al. (2007) and for wheat, maize, sunflower, and rapeseed (but not for all other crops) we assume also adaptation in selecting suitable varieties.

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[11] In the 'Special Report on Emission Scenarios' (SRES), the A1 scenario family describes a future world of rapid economic growth and a rapid introduction of new and more efficient technologies. A1b is a scenario in which a balance between fossil energy and other energy sources is assumed. The A2 scenario family describes a heterogeneous world. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines. The B1 scenario family describes a convergent world with rapid changes toward a service and information economy, a reduction in material intensity, and the introduction of clean and resource-efficient technologies.

[12] Calculations were performed with CCSM3 (Collins et al., 2006), ECHAM5 (Jungclaus et al., 2006), ECHO-G (Min et al., 2005), GFDL (Delworth et al., 2006), and HadCM3 (Cox et al., 1999). For a description of these models see the papers quoted here.

Data on changes in crop yields are presented as region-specific percent change rates. Data were originally calculated at a spatial resolution of 0.5°x0.5° and then aggregated to country-level change rates. We then calculated the arithmetic mean of the change rates in all 15 scenarios with and without $CO_2$ fertilization effect. These country-level results were then used to calculate area-weighted average changes in crop yields in each region (Table 10).

**Table 10. Modelled climate impact on cropland yields in 2050 with and without $CO_2$ fertilization**

| | Mean yield change under climate change 2050 | |
|---|---|---|
| | with $CO_2$ fertilization | without $CO_2$ fertilization |
| Northern Africa and Western Asia | + 4.44 % | - 8.65 % |
| Sub-Saharan Africa | + 8.46 % | - 6.17 % |
| Central Asia and Russian Federation | + 24.91 % | + 5.12 % |
| Eastern Asia | + 11.96 % | - 3.90 % |
| Southern Asia | + 18.45 % | - 15.61 % |
| South-Eastern Asia | + 28.22 % | - 15.83 % |
| Northern America | + 12.45 % | - 6.25 % |
| Latin America & the Carribean | + 12.39 % | - 7.02 % |
| Western Europe | + 16.42 % | + 2.04 % |
| Eastern & South-Eastern Europe | + 19.08 % | - 0.66 % |
| Oceania and Australia | + 0.74 % | - 16.02 % |

Source: Average of LPJmL model runs for 15 climate scenarios for 2050.

We find that the climate change effect on crop yields is highly uncertain. Depending on climate scenario (not shown) and the assumptions on the effectiveness of $CO_2$ fertilization, most regions may experience significant decreases in crop yields as well as significant increases. The most important factor is the uncertainty in $CO_2$ fertilization which is explicitly analyzed here. This effect can principally increase crop yields considerably due to enhanced carbon assimilation rates as well as improved water-use efficiency. Whether or not farmers will be able to attain increased crop yields under elevated atmospheric $CO_2$ concentrations will depend on the availability and cost of additional inputs, especially nitrogen (Tubiello and Ewert, 2002). Increased carbon assimilation rates can only be converted into productive plant tissue or the harvested storage organs if sufficient nutrients are available to sustain the additional growth. Wherever growth is already constrained by nutrient limitations, additional growth will be very limited. On top of that, there is some likelihood that the quality of agricultural products decreases under increased $CO_2$ fertilization, as e.g. the protein content diminishes (Taub et al., 2008). There is also evidence that crops grown under elevated $CO_2$ concentrations might be more susceptible to insect pests (Zavala et al., 2008).

Increasing crop yields may be expected in regions currently constrained by too low temperatures as in the northern high latitudes and in mountainous regions. Here, all 30 model runs uniformly indicate increases in crop yields by 2050. On the contrary, there is hardly any location where all model runs uniformly indicate decreases in crop yields. If all effects of $CO_2$ fertilization are excluded, however, many regions and especially tropical croplands are uniformly projected in all 15 climate scenarios to experience decreases in crop yields. It has to be noted that the beneficial effects of $CO_2$ fertilization are subject to heavy debate (Long et al., 2006, Tubiello et al., 2007).

Results presented here only indicate the order of magnitude of climate-related impacts on crop yields. Besides uncertainties in future development of drivers (climate change, $CO_2$ fertilization effect, management, technological change), modelling of crop yields at large scales adds to the overall uncertainty as many processes are necessarily implemented only in a simplified manner. If farmers have access to a broad selection of crop varieties, they are likely to select varieties most suited for the local growing conditions, which could not be fully considered here.

## Productivity of intensive, humane and organic animal husbandry

This section compares the feeding efficiencies of intensive (industrialised), humane (free-range) and organic livestock systems and quantifies area-requirement for free-range systems. The aim of this section is to derive factors for calculating feed balances of different systems of animal husbandry in the biomass-balance model. We are here only comparing humane (free-range) and organic livestock rearing systems with intensive indoor-housed livestock rearing systems. Note that extensive systems (both subsistence and market-integrated extensive systems) involve a significantly higher amount of grazing and have considerably lower feeding efficiencies than the economically optimised humane and organic systems described here. Subsistence livestock systems are usually multifunctional systems in which livestock serves different purposes (draught animals, social and ritual functions of livestock, etc.) and are not 'optimised' according to criteria such as feeding efficiency. Market-oriented extensive systems are characterised by a very low share of market feed and a high importance of grazing. These systems usually develop where much land is available; accordingly they are optimised with respect to other criteria than feeding efficiency or maximisation of output (e.g. labour efficency, minimisation of commercial inputs).

The comparison of the performance of intensive livestock production versus humane and organic husbandry shows a mixed picture. We analysed the literature regarding cattle, poultry and pig production in various systems. An overview of the results is shown in Table A 10, Table A 11 and Table A 12 in the Appendix. The difference of body and carcass weights of cattle ranges from nearly equal values in organic and intensive systems (Younie, 2001, Kristensen and Kristensen, 1998) to a reduction to 87.8 % for body and 76 % for carcass weights (Neel et al., 2007). Live weight gain of cattle is lowered to 77.1 % (Younie, 2001) for organic breeding systems and the decrease of milk yield per cow shows the following values if organic and extensive systems are compared to intensive ones: 98.4% (Kristensen and Kristensen, 1998), 94.6% (Haas et al., 2001), 90.0% (Padel, 2000), 78.1% (Haas et al., 2001) and 70.7% (Rosati and Aumayr, 2004). A comparison of yield displaying litres of milk per hectare gives a reduction to 75.0% for organic systems (Padel, 2000). Stocking rates are reduced by 23.3% (Younie, 2001) and beef production without intensive use of Nitrogen and irrigation is half as productive as intensive systems (Extensive Agriculture Branch - DPIW, 2009).

Carcass weights of poultry are lower in organic systems (Castellini et al., 2002), but higher for animals with access to outdoor areas (Fanatico et al., 2008). Furthermore animals with outdoor access have a higher feed demand of 16.8% per unit of weight gained (Fanatico et al., 2008).

Live weights, carcass weights, feed intake and growth rate are slightly higher for pigs with outdoor access (Lebret et al., 2006, Gentry et al., 2002, British Pig Executive, 2009). Feed efficiency of pigs (feed per unit of liveweight gain) is lower in humane farming (5.7 to 24.2%, Bornett et al., 2003) and in most cases in organic farming (2.6% to 26.8%, Kirchmann et al., 2008, Bornett et al., 2003).

Considering that these numbers vary broadly (up to 24% production loss for humane farming and up to 30% production loss for organic farming) and are mostly based on farm-level studies, whereas we base our other calculations on top-down data (i.e. country- or even regional-level, referring to entire animal populations, and not only to animals directly involved in output-oriented production) on efficiencies, we conclude that at present no sufficient database exists to comprehensively determine changes in feed efficiencies involved in changes from intensive to humane or organic livestock rearing systems. We therefore used a simplified approach to indicate possible orders of magnitude of changes in feeding efficiency associated with organic and humane livestock systems as compared to intensive systems. We assumed that producing one ton of dry matter of animal product (meat and eggs in the case of pigs and poultry and meat and milk in the case of ruminants) requires

- 10% more inputs (of all kinds, i.e. market-feed and roughage) for humane (free-range) livestock rearing systems
- 20% more inputs (of all kinds) for organic livestock rearing systems

compared to intensive (indoor-housed) industrial livestock rearing systems. The feeding efficiencies of organic systems is assumed to be lower than that of humane systems because IFOAM standards in organic agriculture are stricter than those required to meet standards of humane livestock rearing and the literature review accordingly suggested that feeding efficiencies are lower in organic than in humane systems. Note that this section only compares intensive indoor-housed livestock rearing systems with intensive (efficiency-optimised) humane (free range) and organic livestock rearing systems.

Based on statistical data reported by the FAO and standardized according to methods described elsewhere (Krausmann et al., 2008a) we derived trajectories of the input-output ratios of livestock for the time period from 1961 to 2000 at the regional level (see Figure 5). Using this database, we derived typical input-output values for five different livestock productions systems:

(1) Intensive (industrial), indoor-housed systems
(2) Market-oriented extensive systems
(3) Subsistence livestock systems
(4) Humane farming (free-range)
(5) Organic livestock systems

For each region, we assumed a mix of these five livestock production systems with their corresponding input-output ratios in order to match the current situation; that is, the data displayed in Figure 5 for the year 2000. In building the scenarios, we then assumed changes in the mix of these five livestock production systems. For the intensive animal production scenario ('intensive'), we assumed a reduction of the regional subsistence fraction by 50% in favour of industrial, indoor-housed, or extensive, market oriented production systems. For the humane farming scenario we assumed that humane farming systems replace all industrial, indoor-housed systems, and the same assumption was made for the organic farming scenario. Additionally, it was assumed that in the humane scenario no organic farming systems occur, and, analogously, that no humane systems occur in the organic scenario. Because organic systems adhere to even stricter criteria in terms of animal welfare than humane systems (as well as other criteria not relevant for humane systems), this assumption reflects two possible alternatives of implementing good animal welfare with or without additional environmental or sustainability criteria. Figure 6 shows the resulting global production system mix for 2000 and for the three livestock scenarios.

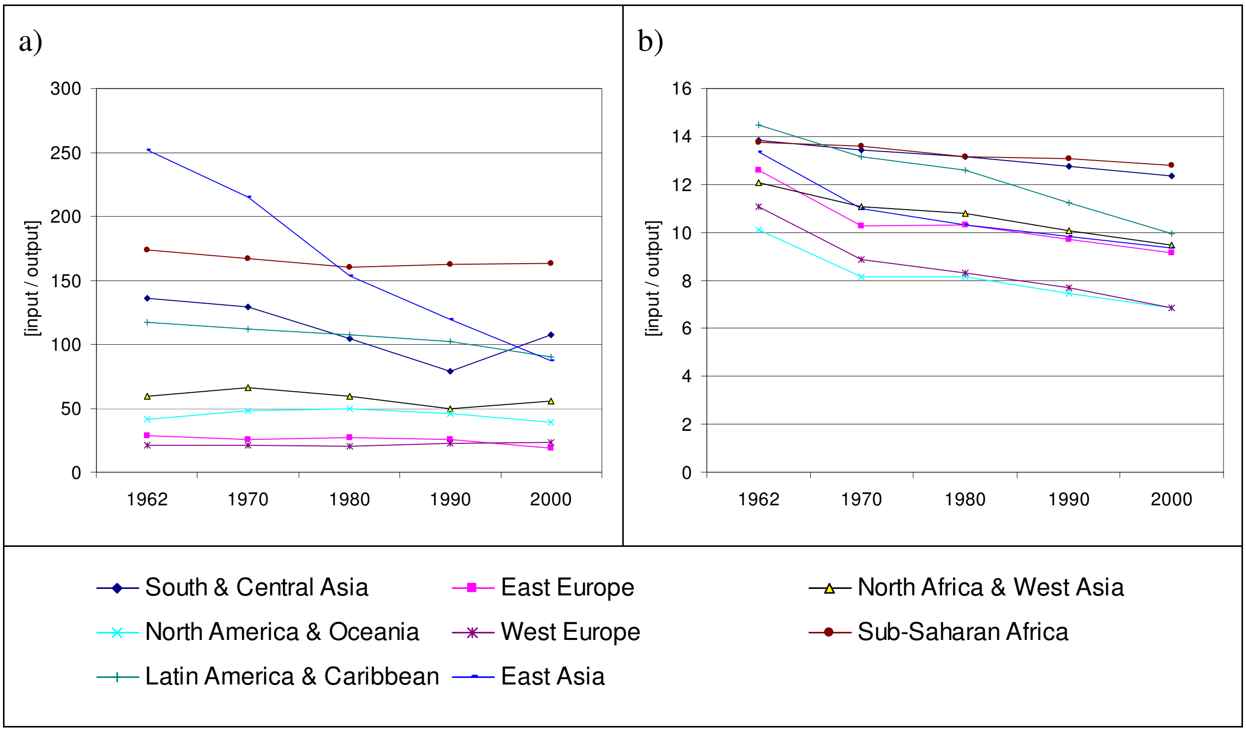


**Figure 5. Development of livestock input-output ratios 1962- 2000. Feed demand of a) Grazers (cattle and buffalo, sheep, goats), b) Non-grazers (pigs, poultry).**

Note that these input-output ratios are top-down derived, i.e. referring to the regional overall feed demand of the entire livestock population, regardless if animals are directly used in the output-oriented production. For details, see text. Note that for this time series analysis it was not possible to follow the regional grouping used in this study.

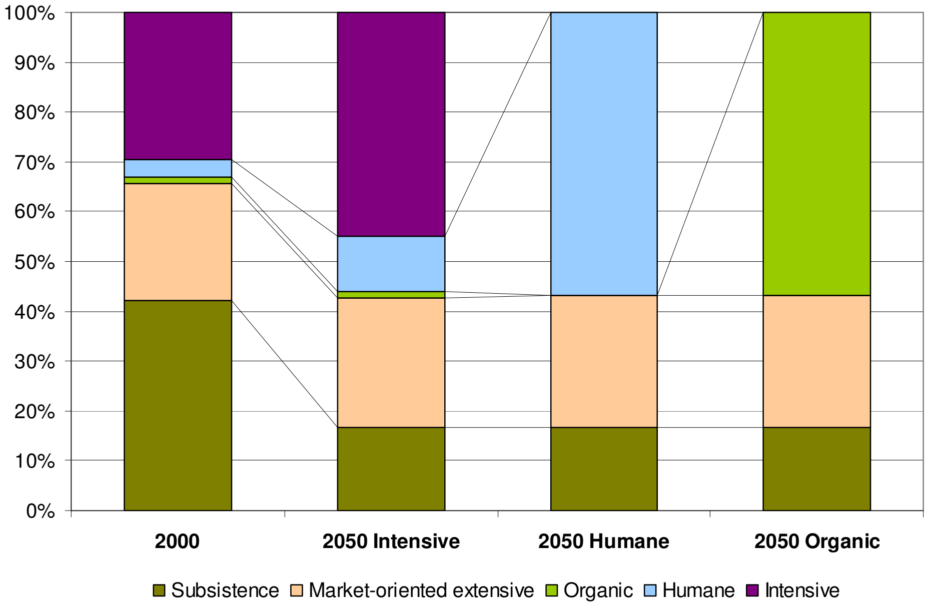


**Figure 6. Mix of livestock farming systems, in 2000 (left column) and the assumptions on changes in this mix used to develop scenarios for 2050.**

Note that optimised livestock systems that involve-free range management are classified as 'humane' in 2000 and in the intensive scenario. For details, see text.

We also considered that free-range systems (humane and organic) require additional land on which the animals are provided freedom to roam. We did not consider this to be relevant for cattle, as cattle usually requires a certain amount of grazing land for roughage on which the animals may also roam. In order to take this additional land demand into account for monogastric species (pigs, poultry, etc.), we used the following assumptions which were based on the UK Code of Recommendations for the Welfare of Livestock for Pig Production (DEFRA, 2003): we assumed a density of 20-30 pigs per hectare, 2.5-3.0 generations per year, 90-110 kg live weight at slaughter which yielded a requirement of 0.42 hectares (±40%) for the production of 1 ton of dry matter of animal product. In all scenarios that involved production of monogastric animal products (i.e., meat of pigs and poultry and eggs) in intensive industrial indoor-housed systems, we considered this additional area demand for free-range (humane and organic) production systems. As intensive monogastric livestock production is mostly located in intensive cropland areas, we assumed that this area reduces the available cropland area in the respective scenarios.

## Global food consumption in the year 2000

*Wealthy versus poor country diets*

In order to understand global food consumption patterns and possible future trends, we combine economic data and data on national diets (FAO, 2006a, GGDC, 2007). It is well known that wealthier countries consume more food per capita, but their diets are also fundamentally different in composition compared to poorer countries. We divide national diets into major food sources: (1) cereals, (2) roots & tubers, (3) pulses, (4) fruits and vegetables, (5) vegetable oils, (6) sugar and sweeteners, (7) animal products (meat, fat, dairy, fish).

Of these food sources, we find that the consumption of the first three categories is clearly lower in countries with a high GDP per capita (Figure 7), and the last three are clearly consumed more in countries with a higher GDP per capita (Figure 8). This leaves fruits and vegetables as the only category without economic dependence. Cereals, roots & tubers and pulses, the staples of poor country diets, tend to be less processed and refined. In contrast, animal products, vegetable oils and sugar / sweeteners, mainstays of rich country diets, are almost always highly processed and refined. In rich countries, animal products are in effect an inefficient processing of cereals and oilcrops.

There is considerable variation in the share within the rich and poor food sources. For instance, some poor countries consume mostly cereals, others use more roots and tubers, and some rich countries consume more vegetable oils, others more animal products, and others sugar & sweeteners. However, the total share of poor country food sources, cereals, roots & tubers and pulses, is a very robust decreasing function of GDP per capita (Figure 7), and the total share of rich country food sources, animal products, sugars / sweeteners, vegetable oils, is a very robust increasing function of GDP per capita (Figure 8).

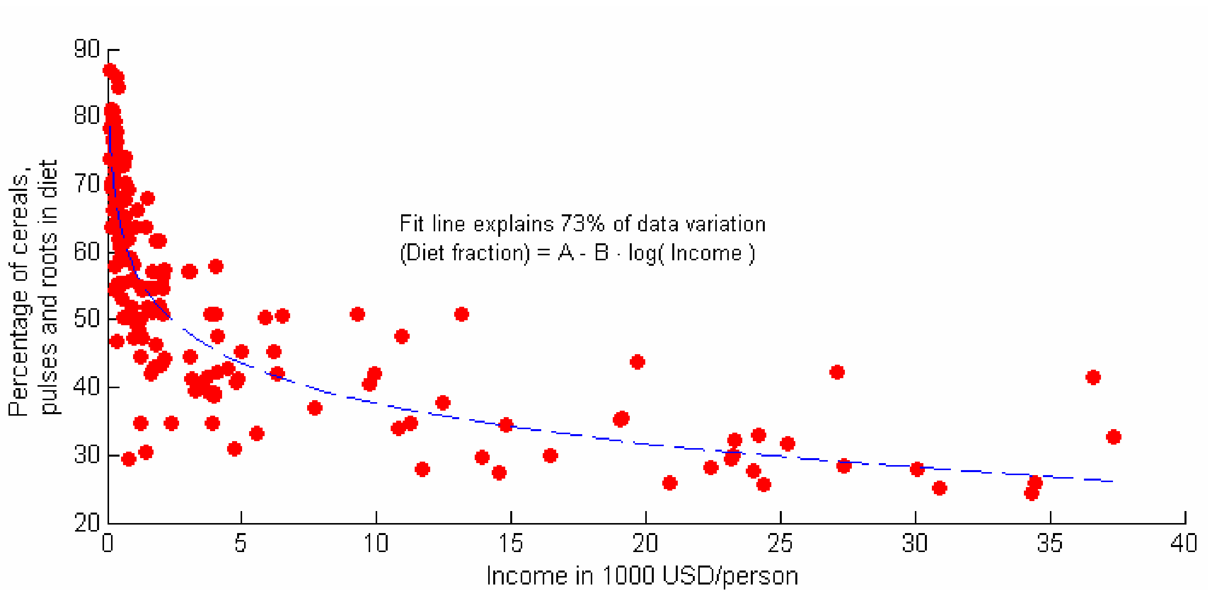


**Figure 7. Share of cereals, pulses and roots in the diet versus income (GDP per capita) in 2000-2003. Each red point represents a country.**

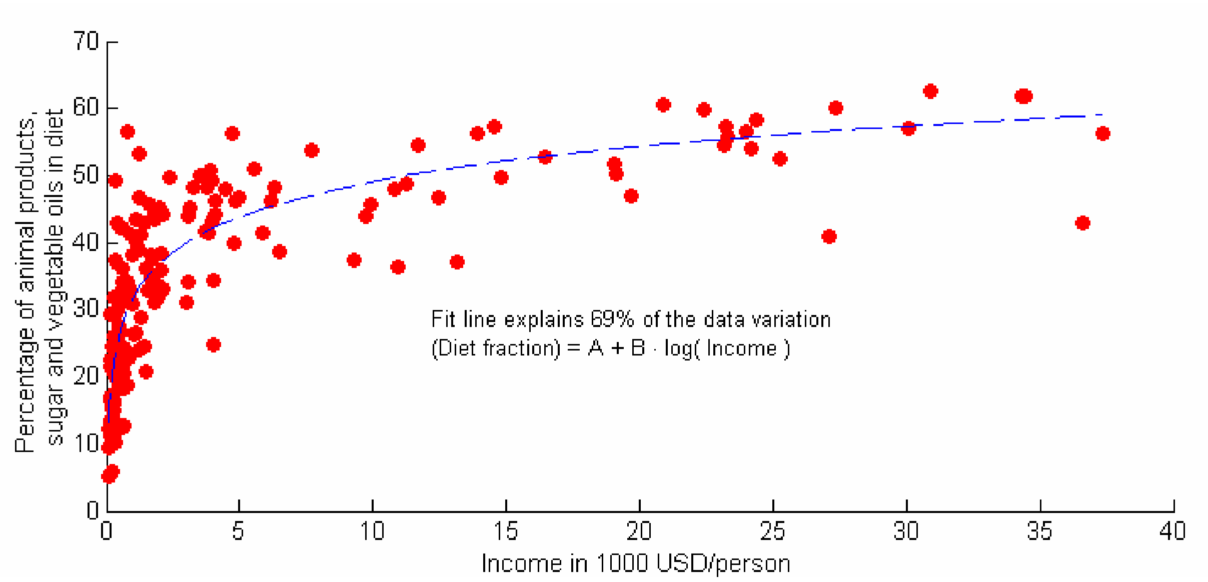
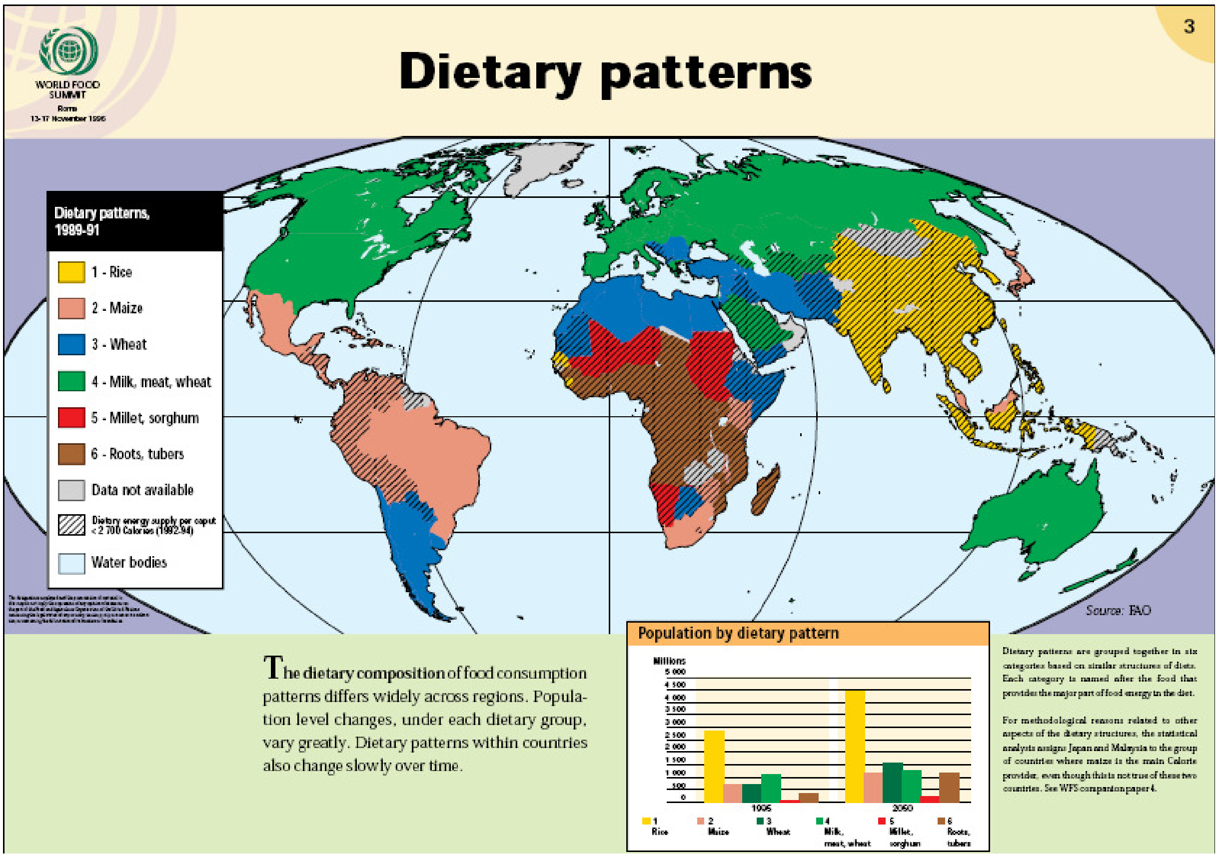


**Figure 8. Share of animal products, sugar and vegetable oils in the diet versus income (GDP per capita) in 2000-2003. Each red point represents a country.**

These results are important in determining the business-as-usual scenario for 2050: if ‘business as usual’ means continued economic growth, we can expect the shares of cereals, roots and pulses to decline, as the share of meat, sugar&sweeteners and vegetable oils grows. Moreover, total dietary energy will also increase.

### *Regional differences in diet in 2000*

Far from being uniform, dietary patterns are known to vary regionally across the globe (Figure 9). Staple crops vary from region to region: maize in Latin America, wheat in North America, Europe, North Africa and Central Asia, rice in South and East Asia, roots and tubers in Sub-Saharan Africa. Moreover, in industrialised regions, staple crops, including those imported from poorer countries or other regions, are being supplanted by, or rather used to produce, animal products. The staple crops and animal products have widely varying nutritional properties, in terms of dietary energy, protein and fat content. We identify and quantify these regional differences in food consumption, in order to maintain an appropriate regional specificity in the 2050 scenarios.



The dietary composition of food consumption patterns differs widely across regions. Population level changes, under each dietary group, vary greatly. Dietary patterns within countries also change slowly over time.

Dietary patterns are grouped together in six categories based on similar structures of diets. Each category is named after the food that provides the major part of food energy in the diet.

For methodological reasons related to other aspects of the dietary structures, the statistical analysis assigns Japan and Malaysia to the group of countries where maize is the main Calorie provider, even though this is not true of these two countries. See WFS companion paper 4.

**Figure 9. Dietary dependence in different geographic regions.**
Source: FAO, 1996

We use data on the global food supply which is compiled by the FAO (FAO, 2005), at the national level, according to roughly 100 food commodity types. For our analysis, we aggregated the detailed food commodities into 11 principal food categories, and aggregate the countries into the 11 regional areas described above. The food categories are the following:

- Cereals (includes beer and alcoholic beverages, except for wine);
- Roots;
- Sugar crops (includes high fructose corn syrup);
- Pulses;
- Oil crops (includes rice and maize oil);
- Vegetables and fruits (includes wine);
- Meat from ruminants;
- Pigs, poultry, eggs;

- Milk, butter, other dairy products excluding eggs;
- Fish;
- Other (includes spices, stimulants such as coffee and cocoa, nuts and honey).

These food categories are designed with respect to the main crop and production categories in order to allow a direct linking to production processes: hence the combination of cereals and beer, fruit and wine, poultry and eggs. However, a few exceptions to this rule are inevitable. For instance, rice and maize oil are grouped with oil crops, and corn syrup included in sugar crops. These exceptions are necessary to understand international dietary patterns and their evolution, where sugar and oil play an increasingly important role, as we have shown above.

Food consumption is measured by the FAO in fresh weight, dietary (nutritional) energy (kcal), protein (grams) and fat (grams), per capita and per day. We combine these quantities, along with dietary measurement factors, to obtain carbohydrate (grams) and total dry weight (grams). The food consumption in dry weight can then be related to the food production in dry weight. The dietary energy and carbohydrate, protein and fat contents are used to generate ratios of protein, fat and carbohydrates per dietary energy content, in grams per kcal, which are unique for each of the 11 regions and 11 food categories (Table A 2). These ratios are used to translate a diet from energy units to protein and fat, in order to ensure that the diet has the correct regional properties, as well as a reasonable dietary composition. In particular, we focus on total dietary energy and protein content of the diets.

The data for the year 2000 is an average over 1999-2001, to smooth over climatic and other extreme events in any given year. The differences between world regions in the composition and magnitude of their diet are striking (Figure 10a). At one end of the spectrum, Sub-Saharan Africa has the lowest-energy diet: at 2 247 kcal/cap/d, far below the minimum recommended 2 500 kcal/cap/d. Sub-Saharan Africa obtains more of its dietary energy from cereals, roots, pulses, vegetables and fruit than North America, although its total dietary energy is only 60% of North America's total. North America's diet is almost evenly spread between animal products, sugar and oil crops, and from cereals, roots, pulses, vegetables and fruit.

The inequality in protein consumption and origins is even starker (Figure 10b). The average North American consumes twice as much protein as the average Sub-Saharan African, and almost two thirds of it comes from animal products, compared to one fifth for Sub-Saharan Africa.

Most regions in the world are somewhere between these two extremes. After North America, Western Europe and Oceania & Australia have the highest-energy diets and animal product fractions of protein, followed by Eastern Europe. Southern Asia, South-Eastern Asia have some of the lowest-energy diets, and lowest protein fraction from animal protein. Sub-Saharan Africa and Southern Asia are both the poorest regions in terms of diets, and the regions projected to have the largest population growth until 2050: both areas are expecting population increases of over 1 billion people. The challenge of feeding the 3 billion humans which will be added to the global population between 2000 and 2050 is thus concentrated in the poorest areas.

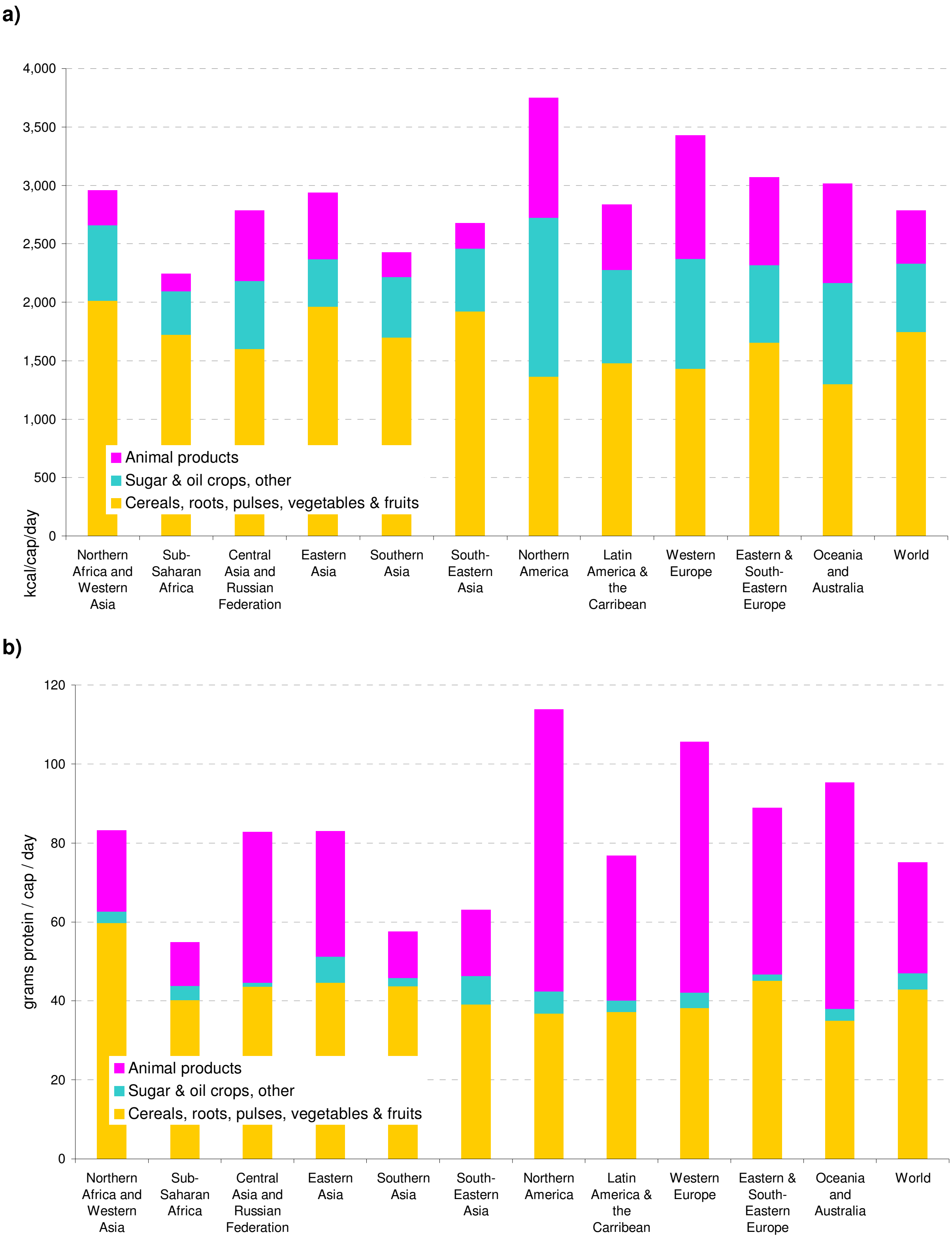


**Figure 10. Global food consumption per capita and day, average of the years 1999-2001. (a) Total calorie intake by 3 food categories, (b) gram protein per capita and day.**

Considering the totality of food consumption and population, in 2000 Sub-Saharan Africa had 11% of the world's population and ate 11% of the cereals, roots, pulses, vegetables & fruits, but consumed only 3% of the world's animal products. In contrast, North America had 5% of the world's population, ate 4% of its cereals, pulses, roots, fruits & vegetables, but consumed

12% of the world's animal products. Of course, if the cereals used to feed animals for human consumption were included, these proportions would increase substantially. For example, South Asia and Sub-Saharan Africa use about 30-35 kg of dry-matter biomass per capita and year as market feed, whereas North America and East and Southeast Europe use 600-650 kg dry matter per capita and year (see Table 5).

## Diet scenarios for 2050

Human food consumption has considerable impacts on the environment (White, 2000). Changes in diet have therefore often been advocated as a means to reduce human pressures on the environment. In particular, on a global level and with continued population growth it might be difficult, if not impossible, to meet any expected future demand for food in terms of quantity and quality with environmentally less detrimental or more humane cropping and livestock rearing technologies. In order to explore such options, we here rely on a scenario approach. We develop four scenarios for regional food demand until 2050 based on assumptions on changes in per-capita consumption of food. For calculating the total volumes of food consumption we use the UN medium variant projections for population as discussed above (Table 6).

- ‘Western high meat’: Economic growth and consumption patterns accelerate in the coming decades, leading to a globalization of western diet patterns.
- ’Current trend’: By 2050, every region is projected to attain the diet level of its country with the highest diet in 2000. This is an economic growth scenario in which present trends are expected to continue into the future.
- ‘Less meat’: The regional diet levels remain at the ’current trend’ scenario levels, but only 30% of the protein comes from animal sources.
- ‘Fair less meat’: There is a universal diet level of 2800 kcal/cap/day, available equitably to the world’s population, with 20% of the protein coming from animal sources.

The motivation behind these four scenarios is as follows. The ’current trend’ scenario continues current economic growth trends: diets, like incomes, are expected to increase and gravitate towards the ingredients preferred by higher income populations: vegetable oil, sugar crops and animal products. If no environmental or economic constraints exist, this scenario is the most plausible one. The ‘western high meat’ scenario assumes economic growth beyond the current trends, and a globalization of the western trend towards high consumption of animal products. The last two scenarios are significant departures from these growth trends. The ‘less meat’ scenario maintains the regional diet inequalities of the ‘current trend’ scenario, but moves to a lower meat diet in western countries, with 30% of the protein in the diet from animal products. This leads to dramatic changes in the composition of many regions’ diets. The lower animal protein requirement is based on environmental concerns: the is the level of consumption of animal products in a diet, the more environmentally sustainable it is. The main reasons for this consideration are (1) the large losses involved in converting plants into animal products; i.e. that animal products require more biomass (and therefore increase all associated impacts such as emissions, pressures on ecosystems and soils, use of water, fertilizers, etc.) and (2) the environmental impacts of livestock (e.g., ammonia and methane emissions, water pollution and others). The ’fair less meat’ scenario goes two steps further. It models a greater shift away from animal products in western countries and even many of the developing countries (only 20% of protein from animal products) and also presumes a fair distribution of the global diet, which is maintained at 2 800 kcal/cap/day, the global average in 2000. These elements are summarized in Table 11.

Both lower meat consumption scenarios would require significant change in public attitudes, supported by massive policy intervention. They are included here to understand the environmental and food security benefits available from a shift away from animal products in western diets, while maintaining human diets at a nutritionally sufficient level in terms of both quantity and quality (i.e. not only energetically sufficient but also in terms of protein and fat).

Regarding one consumption category, we impose a supply restriction on all scenarios. Global fish yields are not expected to increase, and are in fact predicted to decrease due to current overfishing. We assume that the overall regional fish consumption remains the same, resulting in lower fish consumption per capita. In those regions where population decreases (Eastern Europe, the Russian Federation and Central Asia), we maintain fish consumption per capita at its 2000 level. The lower fish fraction in the diet is compensated by increases among the other food categories, according to the specific scenario trends.

**Table 11. Basic characteristics of the four diet scenarios used in this study.**

| Scenario | Global increase in dietary energy | Global increase in protein consumption | Business-as-usual evolution of diet | Global protein from animal products | Globally equitable distribution of food |
|---|---|---|---|---|---|
| Western high meat | X | X | X | 44% | |
| Current trend | X | X | X | 38% | |
| Less meat | X | | | 30% | |
| Fair less meat | | | | 20% | X |

The scenario assumptions are described in detail below. The full regional data, along with the world average, are given in the Annex ('western high meat': Table A 4; 'Current trend': Table A 5; 'Less meat': Table A 6; 'Fair less meat': Table A 7).

### *Scenario 1: Extreme wealth*

The 'western high meat' scenario assumes higher economic growth than the 'current trend' scenario. Regions are categorized into three categories, which attain average diets of 3 600, 3 300 and 3 000 kcal/cap/d respectively, based on their levels in 2000. This represents an extreme increase in diet levels for all regions, except those with the highest diets in 2000. The shares of animal products, sugar and vegetable oil are also assumed to increase (see Figure 11). In this scenario, we depart from the 2000 regional distribution among these categories and increase the share of animal products to be consistent with the diets of industrialised countries and China.

The diet of this scenario brings all regions to high diet levels and industrialised diet patterns. The protein consumption increases dramatically, with all regions at or above 80 grams/cap/d, and a global average of 92 grams/cap/d, far above the 'current trend' level of 79 grams/cap/d. The details of this scenario are given in the annex, in Table A 4.

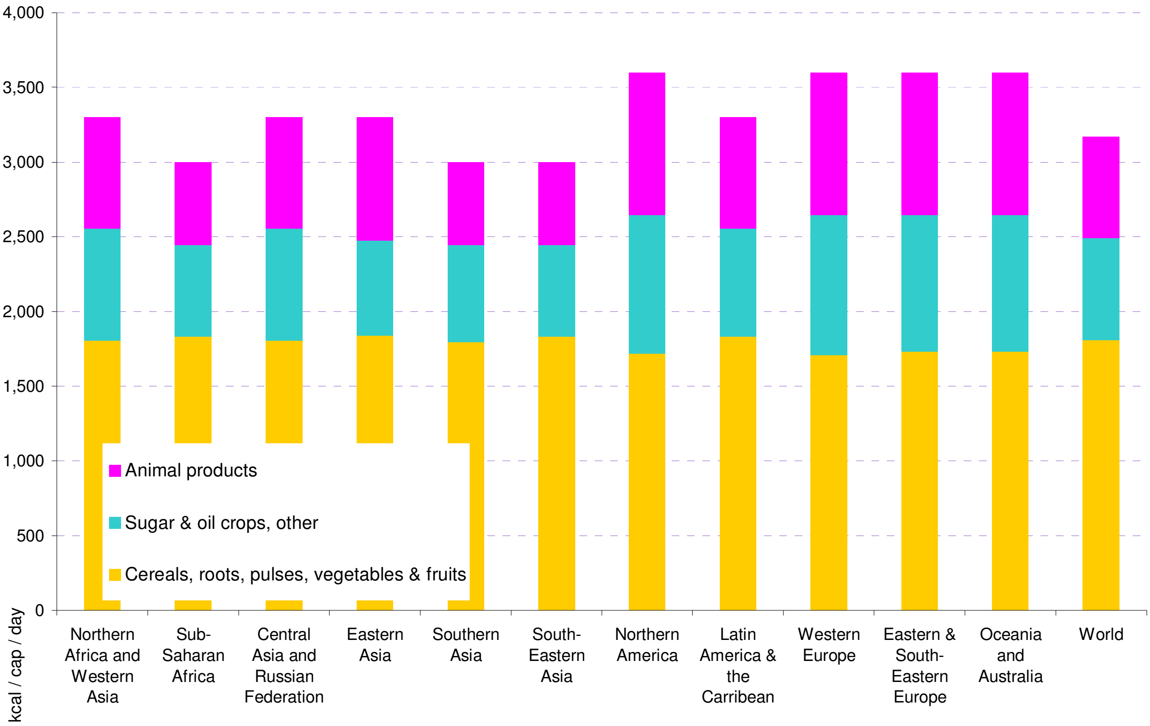


**Figure 11**. **Diets in the 'western high meat' scenario in the year 2050.**

### *Scenario 2: Current trend*

The 'current trend' scenario simulates economic growth by assuming that, by 2050, each regional diet will have caught up to the country in the region with the highest diet in 2000. This 'richest country' (in food terms) is chosen to be representative of the region. The richest country's diet is adapted to the regional pattern, in order to maintain appropriate fractions (for instance for pork meat in the Islamic countries of North Africa and Western Asia), and shown in Figure 12 (details are documented in the Annex, Table A 5). In general, as we have seen, the share of animal products, vegetable oil and sugar and sweeteners increases with income, as cereals, roots and pulses decrease.

The differences between the 2000 and 2050 'current trend' diets are dramatic. In the business-as-usual scenario, all regions have diets above 2 700 kcal/cap/day, and the world average is almost 3 000. The per capita consumption of sugar and oil crops increases by 19% globally, whereas animal products increase by 7%.

The protein consumption in the 'current trend' scenario is also a contrast to the 2000 status: all regions attain protein levels of almost 70 grams per capita per day. In 2000, several protein-poor regions are close to or below 60 grams per capita per day (Sub-Saharan Africa, Southern Asia, South-Eastern Asia). The 'current trend' scenario thus represents a quantitative and qualitative improvement in diets for the poorest areas, while the richest areas do not significantly increase or change their diets.

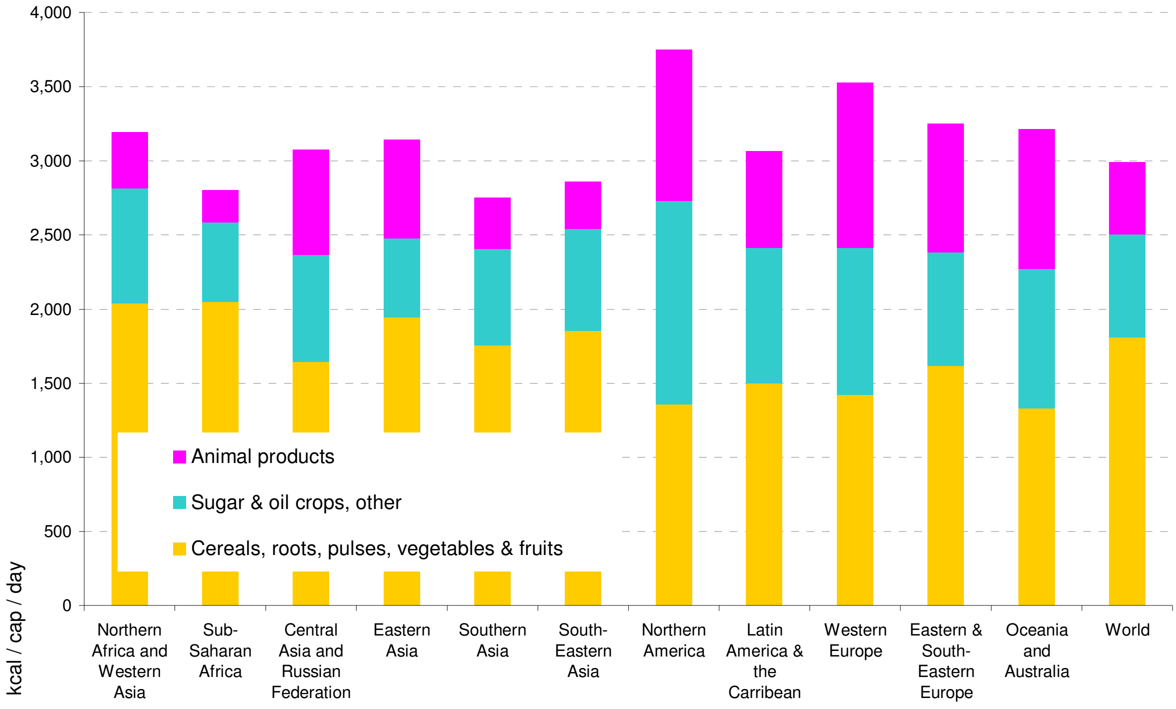


**Figure 12. Diets in the 'current trend' scenario in the year 2050.**

We compared results of our 'current trend' scenario with the demand growth scenarios of the FAO for 2050 (FAO, 2006b), based on the econometric model of Alexandratos, 1995). The results are quite similar, despite the difference in methodology.

Whether and to what extent malnourishment would continue to exist in this scenario depends on the level of within-region inequalities. Currently, the rule of thumb is that malnourishment can only be excluded at a level around 3 000 kcal/cap/day in a larger region, given current levels of inequality within regions. This would suggest that some malnourishment would still prevail in this scenario Sub-Saharan Africa, Southern Asia and South-Eastern Asia, but that the percentage of malnourished people would be considerably smaller in 2050 than today, in accordance with trends for the past decades.

### *Scenario 3: Less meat*

The 'less meat' scenario is based on the idea of satisfying growing food demands, both from population growth and better nutritional levels, by a lower meat diet. By 'less meat', we in fact mean fewer animal products, including fish, milk and eggs. Animal products are especially important for their high protein content per kilocalorie (Table A 3). The only alternative vegetable category is pulses, which in fact have higher protein content than some animal products. The issue of a lower meat diet is thus one of protein levels. In 2000, the lowest share of animal protein was found in Sub-Saharan Africa and Southern Asia, the poorest regions: these only obtained 20% of their protein from animal products. In this scenario, we assume a share of 30% of protein from animal sources to all world regions. As in all scenarios, we make sure that the diet is sufficient in terms of nutrient supply, including protein levels. 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.

The scenario development is iterative, with the following steps: (1) determining total protein quantity; (2) setting the animal protein distribution; (3) setting the vegetable protein distribution; (4) balancing of total calorific intake through the sugar and oil crop categories. Data are displayed in Figure 13 and documented in the Annex (Table A 6).

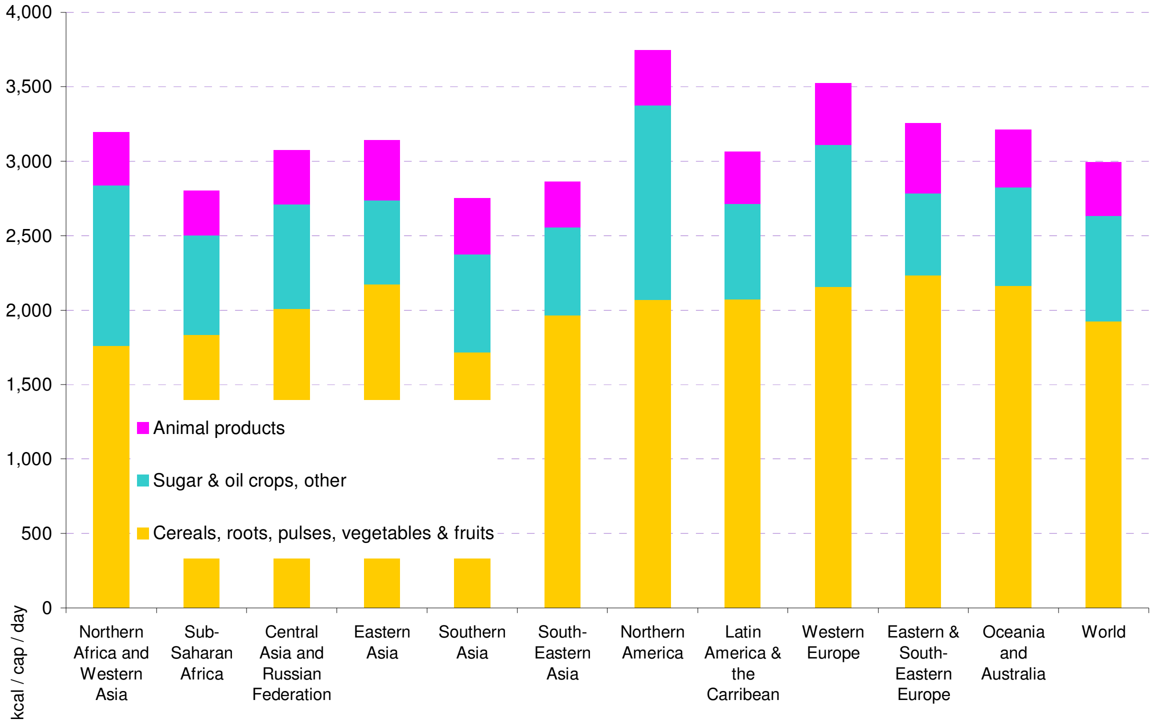


**Figure 13. Diets in the 'less meat' scenario in 2050**

The diet levels are set to be identical in the 'less meat' and the 'current trend' scenarios, but the distribution among food categories changes significantly. The cereals, roots, pulses, vegetables and fruits categories are above 1 700 kcal/cap/d for all regions, even for richer regions where they were lower in 2000, while the animal products, sugar and oil crops shares decrease, in particular in rich regions. The level of protein consumption decreases compared to the business-as-usual scenario. For the poorest regions, the protein level increases compared to 2000; for the richest regions, it decreases, and the world average is maintained at the 2000 level (Table A 6). The diets assumed in this scenario in the different regions are all sufficient in terms of calorie intake as well as protein and fat consumption. As in the BAU scenario, however, malnourishment could only be avoided by a more equal distribution of food in the regions where average calorie intakes are below 3 000 kcal/cap/d.

### *Scenario 4: Fair less meat*

The 'fair less meat' scenario goes beyond the 'less meat' scenario, reducing the fraction of protein from animal sources to 20%. Moreover, in this scenario, we model a fair and equal distribution of 2 800 kcal/cap/d and set protein levels close to 75 g/cap/d. These are roughly the 2000 global average levels. These constraints leave very little room for variation between the world regions, as can be seen in Figure 14. The scenario development is similar to that of the 'less meat' scenario.

The reduction in share of animal protein has significant implications in terms of diet. For instance, if North America were to consume the same quantity of protein as in 2000, but with 80% from vegetable sources, its dietary energy would skyrocket far past 4 000 kcal/cap/d.[13] This diet thus requires a significant decrease in the total amount of protein consumed by the regions with the largest share of animal protein. For these regions, even with a significant decrease in the total protein consumption, the quantity of sugar and vegetable oil in the diet must be reduced in order to keep the dietary energy at reasonable levels. These reductions (in total protein, animal products, vegetable oil and sugar crops) are generally considered beneficial for human health as well as the environment (Duchin, 2005; de Boer et al., 2006; McMichael et al., 2007). The 'fair less meat' scenario also requires a notable increase in the consumption of pulses, which more than double in per capita terms world-wide, compared to their 2000 level of consumption, in order to guarantee a sufficient level of protein supply. The scenario is documented in the Annex (Table A 7).

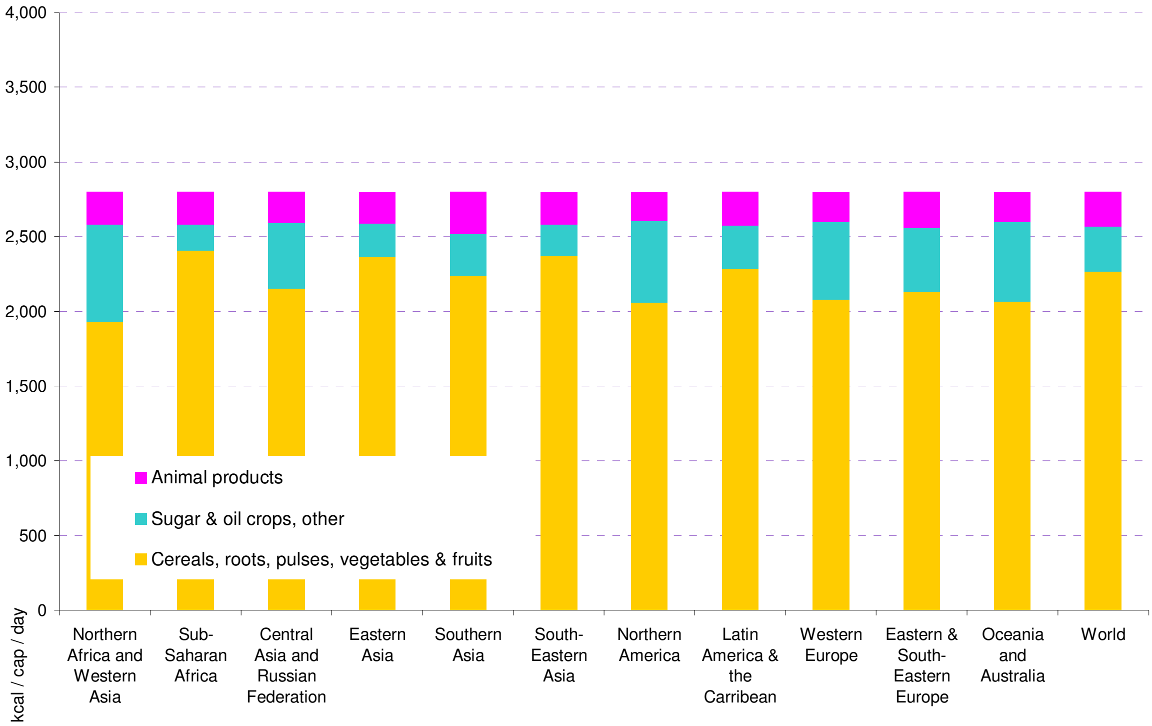


**Figure 14. Diets in the ''fair less meat' scenario in 2050**

An average diet with 2 800 kcal/cap/day and the composition described in Figure 14 would be sufficient for a healthy diet both in terms of quantity and quality (protein level), but only if it were distributed equitably throughout the population. This level of consumption might lead to an undernourishment of up to 10% of the population, if current levels of inequality in food supply between humans within regions would also exist in 2050 (FAO, 2006b). Food consumption depends on income. In order to avoid undernourishment of the poorest populations – today, approximately one billion people, one sixth of the population suffer from poor or insufficient food availability –, it is crucial to address the inequity in food distribution.

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[13] The reason is that plant-based food (except pulses) contains much less protein per kcal, so the nutritional energy of the food that would have to be consumed in order to keep protein levels constant would be exceedingly high.

Achieving a sufficiently equal distribution of food between humans to avoid malnourishment while persuading people now living in regions such as North America or Europe to adopt such a diet, would be a significant social and policy challenge.

In terms of the global quantity of animal products consumed, the scenarios differ considerably. In the ‘current trend’ scenario, the total amount of animal products increases by 62% compared to 2000, and it more than doubles with the ‘western high meat’ scenario. The ‘less meat’ scenario leads to a 20% increase in animal products, despite the lower consumption levels of industrialised countries, because of the increase in consumption levels and population in the poorest areas. In contrast, the ‘fair less meat’ scenario leads to a decrease of 23% in animal products compared to 2000.

## Matching supply and demand: The biomass balance model

### *Matching supply and demand in the year 2000*

In order to evaluate the feasibility of meeting the demand for biomass products resulting from the the four diet scenarios described above with different variants of agricultural technology and cropland area, we developed a biomass balance model. This model calculates the balance of demand and supply of biomass as a function of food and fibre demand, the extent of cropland and grazing areas, conversion efficiencies of the livestock production systems and yields in 2050 (see sections ‘World agriculture towards 2030/2050: An agricultural intensification scenario‘, ‘Yields in organic cropping systems‘ and ‘Productivity of intensive, humane and organic animal husbandry‘).

This biomass balance model is based on an in-depth analysis of biomass flows in the year 2000 and allows the building of consistent scenarios of supply and demand of biomass based on a consistent set of data for 2050. Comprehensive and consistent databases on land use and socioeconomic as well as ecological biomass flows for the year 2000 (Erb et al., 2007, Haberl et al., 2007, Krausmann et al., 2008a, see above) were used to outline a detailed, consistent flow chart of biomass flows, matching demand for final products with gross agricultural production and land use data (see Figure 15). Moreover, the databases available for the year 2000 were used to calculate factors related to the conversion of biomass in food and industrial production as well as livestock input-output rations (e.g. factors concerning conversions efficiencies, seed demand per primary product, losses as fraction of total demand, etc.).

The balance model consists of two distinct calculation pathways, a food crop path (for the demand for cereals, roots and tubers, sugar crops, pulses, oil crops, vegetables and fruits, and other crops, and also for the demand for pig meat, poultry, eggs and fish from aquaculture), and a roughage path (for the demand for meat of ruminants (grazers; ruminant meat, milk, butter and other dairy products).

In the food crop path, the regional demand for final biomass products (e.g. flour, vegetable oils, refined sugar) is compared to the amount of gross primary crop demand (referring to the primary product, e.g. grains, oil-crops, sugar-crops). From this comparison, global factors for estimating the amount of by-products accruing in the course of production of the final product (e.g. brans in flour production from cereals, oil-cakes in vegetable oil production from oilbearing crops), seed requirements and the amount of losses in the agricultural system were derived (see Figure 15).

Monogastric animal species (pigs, poultry) are dealt with within the food crop path as well, because they are fed (mainly) from primary or secondary cropland products. For the demand for final products, i.e. pig meat, poultry, eggs, and fish from aquaculature, the market feed[14] requirement is calculated by applying regional input-output ratios of the monogastric livestock systems (derived from Krausmann et al., 2008a, Wirsenius 2000). 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. Usage factors for these categories were derived from the 2000 database and 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.

The second pathway of the biomass balance model refers to the demand for ruminant meat and milk, and thus to the grazing livestock system. The grazing livestock system is characterized by a demand for market feed (e.g. brans, oil-cakes, cereals) 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). The amount of feed demand per unit of output (meat or milk) varies tremendously between world regions (by a factor of 10, see Figure 5 above), due to the differences in animal husbandry systems. These factors depend particularly on the regional share of subsistence livestock systems (characterized by high input-output ratios for roughage and low input-output ratios for market feed) and industrial meat and milk production (where the opposite holds true, but with much higher overall efficiency due to the higher nutritional value of market feed and a production system optimised for high outputs of protein).

Because the input-output ratios of the different ruminant systems (subsistence, extensive, intensive, etc.) and their prevalence in different regions differ strongly, and considerable amounts of final animal products are traded internationally, it is not possible to derive regional feed demand from the regional consumption of ruminant meat and milk. The reason for this is that such a calculation would assume that each region’s import of animal products is produced in a system that has the same feed efficiency (input-output ratio) as the livestock system of that very region, which would lead to considerable distortions. Therefore we derive regional input-output ratios by comparing the production of ruminant meat and milk to the regional roughage supply, i.e. the sum of grazed biomass, fodder crops and crop residues available in each region. Modulations of these input-output ratios were then used in the 2050 scenario assessment (see below). The amount of crop residues and the fraction used as feed were derived from the database of the year 2000, applying data on harvest indices (the ratio of grain to total plant biomass), data on usage of harvest residues (Haberl et al., 2007, Krausmann et al., 2008a, Wirsenius, 2003) and data on the fraction of available crop residues used for feed. Fodder supply is given in FAO statistics and converted to dry matter using standard tables (Haberl et al., 2007, Souci et al., 2000, Purdue University Center for New Crops and Plant Products, 2006, Löhr, 1990, Watt and Merrill, 1975). The amount of grazing is calculated from grazing land statistic (Erb et al., 2007), the actual NPP of grazing systems and the grazing intensity, i.e. the fraction of grazed biomass to actual NPP in a region, as given in Haberl et al. (2007). The amount of total regional roughage supply in 2000 consistently links to the amount of ruminant meat and milk production in each region, on

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[14] The definition of market feed is given in footnote 3.

basis of the input-output ratio of the livestock systems described above. From the regional ruminant meat and milk production, the regional market feed demand of ruminants is derived and added to the total market feed demand (see above).

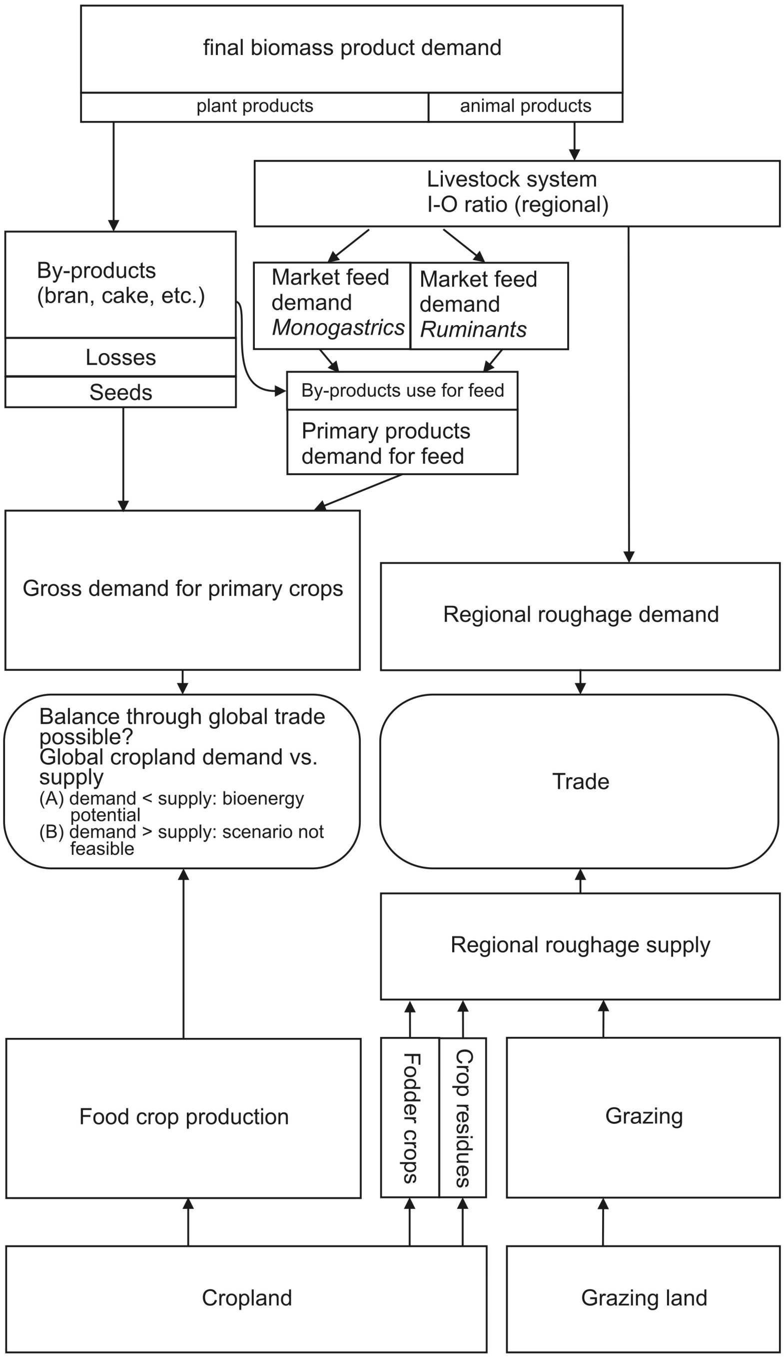

**Figure 15. Flow chart of the biomass balance model used in the study to match agricultural biomass supply and demand.**

The gap between regional supply and regional demand in 2000, for meat as well as for cropland products, is balanced by international 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. Overall, the level of uncertainty of the biomass flow model is at a satisfactory level: extrapolated global demand for gross primary crops is at 98% of the 2000 cropland production, and modelled grazing is at 99% of the grazing amount from the HANPP assessment in the year 2000 (Haberl et al., 2007), the discrepancies owing to the usage of global average factors.

### *Scenario analysis for 2050*

The biomass flow model outlined in Figure 15 utilises data from the databases for the year 2000 (Erb et al., 2007, Haberl et al., 2007, Krausmann et al., 2008a), yield factors on conversion efficiencies, losses and input-output ratios which allow to consistently link demand for biomass products with its associated demand for gross primary agricultural products and with the supply of food crops and roughage in the year 2000.

For the scenario analysis for the year 2050, the following assumptions on diets, land use change, livestock system efficiencies, and cropland yields for the year 2050 were consistently combined (for details on assumptions and data, see above), yielding 72 possible scenarios:

- 4 Diets: (1) Western high meat, (2) Current trend, (3) Less meat, (4) Fair less meat (for a description see section'Diet scenarios 2050').
- 3 Livestock system efficiencies: (1) Intensive (2) humane farming (3) organic farming, with distinct regional input-output ratios of the livestock system (for a description see section 'Productivity of intensive, humane and organic animal husbandry').
- 2 Land use change scenarios: (1) FAO expansion, (2) massive expansion (for a description see section 'World agriculture towards 2030/2050: An agricultural intensification scenario').
- 3 Cropland yields: (1) FAO intensive yields, (2) wholly organic yields, (3) intermediate yields (for a description see section 'Yields in organic cropping systems').

In the data-derived biomass balance model for the year 2000, agricultural biomass supply and demand match by definition, with only negligible deviations resulting from the use of global average factors (see above). Regional differences in supply and demand are balanced by trade. For the 2050 scenario analysis, supply and demand deviate due to changes in demand as well as changes in the agricultural production systems. Two different balancing schemes were followed for the roughage and for the food crop pathway (see Figure 15) in matching supply and demand.

In the roughage pathway, two different outcomes may be achieved when comparing global demand for ruminant products (meat and milk) and the global ruminant product supply. These two cases result from the biomass balance model's architecture, which determines regional meat production as a function of regional roughage supply. Regional roughage supply consists of the supply of fodder crops, crop residues used as feed, and grazing. Whereas fodder crops and crop residues used as feed can be calculated as a function of cropland production, no information is available for grazing in 2050, and thus it is not possible to close the feed balance (matching feed demand and supply, see Krausmann et al., 2008a). Therefore, in a first step we combine grazing land in 2050 with data on aboveground NPP of grazing land and the grazing intensity for the year 2000, derived from (Haberl et al., 2007) in order to calculate a preliminary roughage supply. This roughage supply is then used to calculate an 'interim' regional meat and milk supply, applying regional livestock input-output ratios for the year 2050. This meat and milk supply then is compared to the 2050 global meat and milk demand, resulting in one of the two following outcomes:

(a) Global demand for ruminant products is larger than the calculated 'interim' supply. This can be a consequence of increased demand for animal products, but also due to the reductions in the availability of grazed biomass due to reductions of grazing land in the course of cropland expansion (as we assume all cropland expansion to occur on grazing areas, see section 'Cropland potentials'), or the combination of both effects.

(b) Global demand for ruminant products is smaller than the calculated 'interim' supply. This can be a result of reduced meat and milk demand in some scenarios, but also an effect of increased efficiencies (smaller input-output ratios) of the regional livestock systems.

Case (a) requires an upward adjustment of the interim global ruminant meat and milk supply. The additional amount of roughage required for sustaining the production of additional meat and milk is calculated in the following way. The surplus demand is converted to surplus roughage demand by applying global industrial, humane or organic input-output ratios of the livestock systems. Thus, in this calculation, we assume that the additional meat demand is met by market-oriented, and not by subsistence-based farming systems. The additional roughage demand resulting from this calculation is then allocated to the individual regions according to their free grazing potential. The free grazing potential is calculated by subtracting the amount of biomass grazed in each region from its total grazing potential. The total grazing potential is calculated by assuming a maximum exploitation rate for grazing land (i.e., the ratio of aboveground $NPP_h$ to aboveground $NPP_{act}$) for the four grazing classes: 70% for class 1, 55% for class 2, 40% for class 3 and 20% for class 4. This implies that, in our calculation, regions with larger free potentials for grazing produced a larger share of the global surplus demand than regions with small potentials. This calculation scheme therefore results in an increase of the overall regional grazing intensity.

In case (b), global ruminant product demand is smaller than global 'interim' supply. Therefore, roughage supply has to be reduced in case (b). To achieve this, we assume that all regions reduce grazing according to the fraction of their individual contribution to the global amount of grazing in 2000. In consequence, grazing intensity is reduced in case (b) in all regions.

Note that, following these calculation pathways, the balancing of ruminant meat and milk supply and demand occurs at the global level. Trade is assumed to balance regional disparities of supply and demand.

The food crop pathway is used to assess whether a scenario is feasible or not in terms of the ability of the production system to match global food demand. In this pathway, the modelled primary crop demand (a function of diet and the efficiency of the livestock system) is converted to the required land use by applying the corresponding yields of each scenario, and then compared to the availability of cropland in the scenarios. Scenarios where global cropland requirement exceeds cropland availability by more than 5% are considered as not feasible. Scenarios where requirement and availability deviate within a range of +/- 5% are considered as being probably feasible ('too close to call', i.e. within the uncertainty level of the model). All other scenarios are classified as feasible.

### *Calculation of bioenergy potentials*

For those scenarios where cropland availability according to our assumptions on cropland expansion (FAO business as usual versus massive expansion) exceeds the cropland requirement by more than 5%, a bioenergy potential on cropland and grazing land is calculated. Our calculation of bioenergy supply potentials distinguishes between three fundamentally different production pathways:

- **Bioenergy crops on cropland.** We assume that the entire cropland area available after the area required to supply food, feed and fibre has been subtracted from total cropland in a specific land use scenario can be used to produce bioenergy crops. We calculate the the bioenergy potential on these areas by assuming that bioenergy crops can reach the same productivity as potential vegetation, i.e. by assuming an aboveground NPP equal to that of potential vegetation ($NPP_0$). We assume that the entire aboveground biomass at harvest can be used to produce bioenergy. We then calculate the gross energy potential of these plants by assuming a gross calorific value of 18.5 MJ/kg. Note that this calculation yields a gross supply potential for biomass and does not take conversion or production losses into account. The bioenergy potential would be drastically (50-75%) lower if, for example, the area were used to produce first generation biofuels. In producing these fuels, only parts of the plant can be used. Moreover, their production chains from primary plant material to liquid fuels entail considerable losses (Field et al., 2008, Campbell et al., 2008, WBGU, 2008). Thus, the bioenergy potential resulting from this calculation represents a maximum estimate. It depends on the technology used to convert biomass into final or useful energy which amount of energy can be actually provided. For example, if the total amount of aboveground biomass is harvested and burned ‘as is’ (e.g., combustion of solid biomass in cogeneration plants), the amount of biomass energy that can be produced is close to that potential, while the amount of energy supplied may be only a small fraction if first-generation biofuels are produced.
- **Energy potential from unused residues on cropland.** Crop residues are calculated by applying harvest indices and usage factors derived from (Krausmann et al., 2008a). Crop residues are used as feedstuff and for bedding. The bedding requirement was estimated by calculating the amount of manure produced by livestock, and applying factors to estimate bedding demand from indoor manure production, derived from (Krausmann et al., 2008a). We assumed that 50% of the remaining residues are required to maintain soil fertility and can therefore not be used to produce bioenergy (WBGU, 2008). We are aware that this is a very crude assumption and that higher or lower shares of the residues might be required to maintain soil fertility in different regions, depending on soil and climate conditions (Lal, 2005). Nevertheless, our calculations suggest that this is a significant potential, so in-depth assessments of options to combine bioenergy production and soil fertility management (e.g., energy production through biogas production that maintains a large proportion of the nutrients and parts of the carbon) should be investigated and might emerge as an important option for an integrated optimization of food and energy production (known as ’cascade utilization of biomass’, see Haberl and Geissler, 2000, Haberl et al., 2003, WBGU, 2008). Of course, this is again a gross primary biomass energy supply calculation; the same caveats with respect to conversion losses apply as for the other potentials given here.
- **Bioenergy crops on current grazing areas**. We assume that grazing land in the quality class 1 is also suitable for production of bioenergy crops such as switchgrass (*Panicum virgatum*), other perennial grasses such as *Miscanthus sp.*, short-rotation coppice/forestry or others. In order to calculate the potential of producing such crops on grazing land, we proceeded as follows. On grazing land in quality class 1, the most productive grazing land class, we assumed grazing to take place at the maximum intensity, with an exploitation rate at 67% of the actual aboveground NPP for developing and 75% for industrialised regions. Because the calculated actual exploitation rate is significantly lower than this threshold in most regions, this assumption implies that a significant fraction of the area extent of grazing class 1 can be used for bioenergy crops without reducing regional roughage supply. On this area, the bioener-

gy potential is approximated as the current aboveground NPP; that is, we assume that bioenergy crops produce the same amount of aboveground biomass as the current vegetation (see Campbell et al., 2008 and Field et al., 2008 for a justification of this assumption). Factors of actual aNPP are taken from our HANPP database (Haberl et al., 2007). The gross energy potential of this annual biomass production is then calculated by assuming a gross calorific value of 18.5 MJ/kg. Again, this calculation yields a hypothetical maximum energy potential, as discussed above (see 'bioenergy crops on cropland').

As indicated above, if demand for cropland area exceeds the area of cropland considered to exist in a scenario by less then 5%, we consider this scenario to be 'probably feasible' because we did not assume that our model is able to effectively distinguish the result from nil. However, if demand for cropland was larger than the cropland area in a scenario, we calculated the 'cropland biomass deficit' (i.e., the amount of dry-matter biomass required to close the balance) and assumed that this amount of biomass would have to be produced elsewhere, e.g. on grazing land. In this case, we therefore deducted the lacking amount of cropland biomass from the bioenergy potential on current grazing areas (which was calculated as discussed above), assuming that this scenario would require the production of this lacking biomass on grazing areas.

Note that calculations of bioenergy potentials do not include bioenergy potentials from forests. In the year 2000, primary harvest of wood fuels in forests contributed approximately one half to the total supply of bioenergy which amounted to approximately 45 (±10 EJ/yr, 1 EJ = $10^{18}$ Joules, units see Appendix). The amount of fuel wood used in the year 2000 according to FAO figures (FAO, 2004) has a gross calorific value of 22.1 EJ (Krausmann et al., 2008a), whereas the IEA reports that the total amount of 'primary solid biomass' used for energy production globally was 39.4 EJ (IEA, 2007a, IEA, 2007b). We interpret that as an indication that the category 'primary solid biomass' contains other sources of bioenergy than fuel wood; perhaps energy from residues, by-products from agriculture and forestry, manure or other biogenic wastes. Unfortunately, we were not able to find a comprehensive explanation for these inconsistencies between forestry and energy statistics, and it is well known that these data are highly uncertain and bear considerable error margins (Scurlock and Hall, 1990, Turkenburg, 2000, Smeets and Faaij, 2007). In the absence of better data we assume that the three potential sources of bioenergy which we treat in this study (bioenergy plants and residues/wastes from agriculture) might have delivered around 10-25 EJ of energy globally in the year 2000; results for 2050 might be compared against this estimate.Quantifying bioenergy potentials from forestry is beyond the scope of this study. For some additional information on bioenergy potentials in forests see the Appendix.

# Feeding and fuelling the world: Results of the scenario analysis

We here present results from our modelling exercise. Starting from different assumptions on the demand for agricultural products according to four diets in the year 2050 (see above), three assumptions on agricultural yields, three assumptions on livestock farming systems, and two assumptions on land-use change, we calculated 72 scenarios and classified them as 'feasible', 'probably feasible' or 'not feasible' according to their balance of cropland area requirement and availability. The matching of supply and demand follows a 'food first' approach; that is, in a first step we assessed whether a combination of assumptions for diet, yields, cropland expansion and livestock system was feasible or not (i.e. was able to produce the required amount of final food products). Our feasibility criterion was that the demand for cropland was not allowed to exceed cropland available in each scenario by more than 5%. If the difference was below that threshold we assumed that it was too small to be considered different from nil, in which case we classified the scenario as ‘probably feasible’. For all ‘feasible’ and ‘probably feasible’ scenarios, bioenergy potentials were calculated.

Note that scenarios may be unfeasible (or undesirable) for other reasons than insufficient cropland area (i.e. impossibility of closing the balance between supply and demand in our model). For example, it might be impossible to actually achieve yield levels as foreseen by the FAO for the year 2050. This might have economic reasons (e.g. lacking investment, see Kahn et al., 2009) or biophysical reasons (e.g. soil erosion, climate change, lacking water availability, physiological constraints of crop plants, etc.). Much will depend on the extent to which possible constraints can be overcome or at least mitigated through appropriate strategies for agricultural research and knowledge development, which must be seen as a complex system with a trajectory that is hard to predict (IAASTD, 2009). Feedbacks such as possible future reductions in yield levels resulting from poor management or inappropriate agricultural technologies – e.g., deterioration of soils due to unsustainable cropping practices, salinization resulting from poor irrigation techniques, etc. – could not be considered here. Determining the infeasibility of scenarios for such reasons is outside the scope of this study.

## Feasibility analysis of production and consumption systems

Table 12 gives an overview on the feasibility of the different scenarios. Scenarios which are not feasible are left blank in the table. All ‘feasible’ and ‘probably feasible’ scenarios are coloured. The table discerns scenarios that are ‘probably feasibly’, i.e. fall within the uncertainty range of the model and data (+/-, yellow), scenarios classified as ‘feasible’ in which demand for cropland is at least 5% lower than cropland area (+, green), and scenarios where only 80% or less of the extent of cropland in 2050 according to the scenarios is used (++, blue). The scenario assumptions are described in detail above. Here we give a summary of the assumptions used:

- **Yields:** ‘FAO intensive’ refers to the yield levels projected by the FAO for 2050 which are very, perhaps unrealistically high. ‘Wholly organic’ refers to 100% organic cropland agriculture; ‘Intermediate’ is the arithmetic mean and might be interpreted as a 50% organic : 50% intensive scenario or as a scenario in the yield levels forecast by the FAO cannot be achieved or are foregone for ecological reasons.
- **Land use change:** In the ‘business as usual’ (BAU) scenario, global cropland area increases by 9%, in the massive land-use scenario by 19%. Cropland area is assumed to expand into grazing land of the best available quality class.
- **Livestock system:** All scenarios involve a mixture of subsistence systems, extensive market-integrated systems and optimised systems. ‘Intensive’ means that most of the indoor-housed animals are kept in intensive, high input-high output livestock rearing systems whereas humane and organic systems will have very low shares in the market. ‘Humane’ means that 100% of the animals in optimised systems are kept according to standards similar to UK and European free-range standards for humane animal rearing systems, in particular with respect to access to outdoor areas. ‘Organic’ means that 100% of all animals in optimised systems are kept tostandards similar to those proposed by IFOAM for animal husbandry; this includes access to outdoor areas, among other criteria. Assumptions on subsistence and market-integrated extensive systems are not affected by the choice of the optimised livestock rearing systems.
- **Diet**: ‘Western high meat’ is characterized by very high dietary energy and 44% of protein from animal products; ’current trend’ is characterized by high dietary energy

> and 38% of protein from animal products, 'less meat' has the same level of dietary energy as 'current trend' but only 30% of protein from animal products, whereas 'fair less meat' adopts a global level of 2 800 kcal/cap/day and 20% of protein from animal products. All diets are, in principle, sufficient in terms of quantity and quality (sufficient protein and fat). Whether they are also sufficient in terms of eradicating malnourishment depends on distribution of food among people; therefore the 'fair less meat' diet is modelled to require a much more egalitarian distribution of food.

Out of the 72 scenarios, 44 are 'feasible' or 'probably feasible'. Details on these 44 scenarios can be found in

Table A 13 in the Appendix.

**Table 12. Feasibility analysis of all 72 scenarios.**

| | **Crop Yields** | FAO intensive | FAO intensive | Inter-mediate | Inter-mediate | Wholly organic | Wholly organic |
|---|---|---|---|---|---|---|---|
| | **Land use change** | Massive | Business as usual | Massive | Business as usual | Massive | Business as usual |
| **DIET** | **Livestock System** | | | | | | |
| Western high meat | intensive | +/- | - | - | - | - | - |
| Western high meat | humane | - | - | - | - | - | - |
| Western high meat | organic | - | - | - | - | - | - |
| Current trend | intensive | + | + | + | +/- | - | - |
| Current trend | humane | + | + | + | +/- | - | - |
| Current trend | organic | + | +/- | +/- | +/- | - | - |
| Less meat | intensive | + | + | + | + | +/- | - |
| Less meat | humane | + | + | + | + | +/- | - |
| Less meat | organic | + | + | + | + | - | - |
| Fair less meat | intensive | ++ | + | ++ | + | +/- | +/- |
| Fair less meat | humane | ++ | + | ++ | + | +/- | +/- |
| Fair less meat | organic | ++ | + | ++ | + | +/- | - |

The table indicates which combination of assumptions on yields, land use change, characteristic of the livestock system, and diet are classified as 'not feasible' (blank), 'probably feasible' (+/- 5% cropland demand vs. availability, yellow) and 'feasible' (+ green and ++ blue, the latter meaning that cropland demand is <80% of cropland availability).

The feasibility analysis reveals that the 'western high meat' diet, characterized by a high consumption level of animal products and average per-capita diets between 3 600 and 3 000 kcal per day, would only be possible with a combination of massive land use change, intensive livestock production systems and intensively used arable land (FAO intensive yields). Even under these massive assumptions, the model accuracy does not allow to judge unambiguously if the scenario will be feasible or not, and is thus classified only as 'probably feasible'. On the other hand, the world average in 2050 in this case does not even reach the level of current diets in the world's richest regions, so we can conclude that a global convergence towards the average diets enjoyed today in the world's richest regions does not seem feasible from a biophysical perspective.

The 'current trend' scenario, with a global average of 3 000 kcal/cap/day and a considerable growth in the global average protein from animal products, can be realized with several different combinations of yields, livestock system and land-use change. This diet is feasible over the whole range of assumptions on the conversion efficiencies in the livestock system (intensive, humane and organic), but it clearly requires at least crop yield increases as assumed in the 'intermediate' yield assumption. Even with massive land-use change, this diet cannot be sustained in a 'wholly organic' yield assumption. With intermediate crop yields the diet drops from the 'feasible' to the 'probably feasible' category if we move from the massive to the BAU land-use scenario. With organic productivities in the livestock system, the feasibility of producing enough food to sustain such a diet is only classified as 'probably feasible' under all assumptions involving 'FAO intensive' or 'intermediate' yields except for the case with massive land use change and FAO intensive yields (when it becomes 'feasible'), but is 'unfeasible' with 'wholly organic' cropland yields. Large bioenergy potentials on cropland could only be achieved when combining intensive modes of production in livestock, crop yields and massive land use change.

The 'less meat' diet assumes the same level of calorie intake as the 'current trend' scenario, but assumes a reduced share (-26% globally) of animal products. This demand scenario has a much broader feasibility space than the 'current trend' scenario. It is classified as 'feasible' over the whole range of assumptions on livestock system and land-use change for both 'FAO intensive' and 'intermediate' crop yields. In addition, it was even classified as being 'probably feasible' in the 'wholly organic' yield scenario in the case of intensive and humane livestock rearing systems under the assumption of 'massive' land-use change. However, this diet scenario is classified as being 'not feasible' with a 'wholly organic' system in terms of both crop yields and livestock rearing, even with 'massive' land-use change.

The 'fair less meat' diet scenario which assumes a globally equitably adopted diet with 2 800 kcal/cap/day and only 20% of the protein coming from animal products would require much lower increases in yields. It is feasible for all combinations of land-use change and livestock systems with 'intermediate' yields, and even more so with 'FAO intensive' crop yields. It was classified as 'probably feasible' with 'wholly organic' cropland yields for all assumptions on livestock rearing, except in the case of BAU land-use change which was not classified as being feasible in combination with the feeding efficiencies assumed in the organic livestock scenario. Of course this might change if higher yielding variants of organic cropland farming than we assume here can be developed in the future (but remember that we assume a continuation of the growth in crop yields in many regions even in that scenario, see Figure 4).

We conclude that providing enough food (not only calories, but also protein and fat) for a world with 9.2 billion inhabitants based on 'wholly organic' cropland and livestock systems seems 'probably feasible' based on an increase of global cropland area of approximately 20% if people would adopt a diet with no more than 20% of protein from animal sources at a level of 2 800 calories per capita and day. The level of calorie intake is similar to the globally average diet in the year 2000. This level is, in principle, sufficient to provide enough food for anyone, with malnourishment excluded under this assumption through equal distribution among the global population. If equal distribution cannot be achieved, however, malnourishment cannot be excluded at that level of average calorie supply.

The 'wholly organic' assumption on crop yields is fairly radical in that it assumes that 100% of the cropland is cultivated according to organic standards. We find it reassuring that 'intermediate' yields seem sufficient or at least probably sufficient to support a 'current trend' diet, irrespective of the livestock rearing systems assumed, and highly sufficient for the 'less meat' diet. This means that prospects are good that it will be possible to feed the world even if the very high yields assumed in the FAO intensive crop scenario cannot be realized, or if they can, it would be possible to achieve a reasonable level of food supply based on a significantly larger proportion of organic and environmentally friendly agriculture. Consequently, there is no necessity to go for the highest possible yields or maximize cropland area at all costs, irrespective of the environmental, economic, social, and health impacts involved in doing so – in contrast, our calculations suggest that the world can afford to forego some potentially possible intensification without jeopardizing world food supply. However, this might have implications for the amount of bioenergy that can be supplied, as discussed in the next section.

## Tradeoffs between bioenergy, land-use change and yield levels

Our calculations clearly show that the amount of bioenergy that can be produced in a scenario grows with higher yields and higher feeding efficiency of livestock. By contrast, the bioenergy potential shrinks when higher amounts of food consumed in general and animal products in particular (see Table 13 and Figure 16). Cropland expansion has a lower impact: on the one hand, it increases the bioenergy potential on cropland, but on the other hand it reduces the bioenergy potential on grazing areas. The highest bioenergy potential (161 EJ/yr) is found in a scenario with the highly unlikely combination of 'FAO intensive' yields, 'intensive' livestock systems, 'massive' land use change, and a 'fair less meat' diet. The lowest bioenergy potential (58 EJ/yr) is found in the only feasible scenario that succeeds in supporting the 'western high meat' diet.

Table A 13 in the annex provides the respective data for all scenarios, classified as 'feasible' or 'probably feasible'.

Table 13 compiles some results for four selected scenarios. The first part of the table shows that the mass of food consumed globally does not differ drastically between the scenarios (all being in the range of 2.3-2.5 billion tons of dry matter) – after all, the amount of biomass humans can ingest is limited by physiological constraints –, but the composition varies considerably: While the world consumes 367 million tons dry matter of animal products in the 'western high meat' scenario, the respective figure is 264 mio. t/yr in the 'current trend' diet, 198 mio. t/yr in the 'less meat' diet and 130 mio. t/yr in the case of the 'fair less meat' diet.

The second part of Table 13 shows the composition of the bioenergy potential; that is, the size of the three fractions (bioenergy crops on cropland, residues from cropland and bioenergy potential on grazing land). The potential to grow bioenergy crops on cropland depends strongly on diet and yields. This potential can become negative if demand for biomass from cropland exceeds the production of biomass on cropland by less than 5%; i.e. where bioenergy production on cropland is not possible. We classified such scenarios as 'probably feasible', assuming that the difference from zero (closed balance) was not significant given the many uncertainties in our biomass balance model. We nevertheless subtracted this amount when calculating the total bioenergy potential, reflecting the fact that in such a scenario some additional biomass would have to be produced somewhere else than on cropland, most probably on grazing land of quality class 1, so that this area would not be available for additional bioenergy production. Residue potentials and potentials for bioenergy production on grazing land of quality class 1 strongly depend on the global consumption of animal products for food: if the consumption of animal products is low, much less of the residues from cropland is required for the animal system; this increases the bioenergy potential from residues. Moreover, grazing intensity is also lower if the consumption of animal products is lower, therefore leaving more space to plant bioenergy crops on grazing areas, resulting in a higher bioenergy potential.

**Table 13. Bioenergy potentials and some other data for selected scenarios**

| Diet | | Western high meat | Fair less meat | Current trend | Less meat | Fair less meat |
|---|---|---|---|---|---|---|
| Livestock system | | Intensive | Intensive | Intensive | Humane | Organic |
| Crop yields | | FAO | FAO | FAO | Interm. | Interm. |
| Land use | | Massive | Massive | BAU | BAU | Massive |
| Vegetable Food | [1000 tdm/yr] | 1.958 | 2.093 | 1.964 | 2.065 | 2.093 |
| Animal Products | [1000 tdm/yr] | 367 | 130 | 264 | 198 | 130 |
| Others (Fibres etc.) | [1000 tdm/yr] | 143 | 122 | 121 | 124 | 122 |
| **Food total** | **[1000 tdm/yr]** | **2.468** | **2.345** | **2.349** | **2.387** | **2.345** |
| **Bioenergy potential** | | | | | | |
| Bioenergy crops on cropland | [1000 tdm/yr] | -562 | 2.855 | 971 | 1.051 | 2.814 |
| Residues from cropland (excl. bedding and 50% for soil conservation) | [1000 tdm/yr] | 1.639 | 1.955 | 1.494 | 1.270 | 1.522 |
| Bioenergy potential on grazing land (gross) | [1000 tdm/yr] | 2.053 | 3.885 | 3.194 | 3.334 | 3.139 |
| **Bioenergy total** | **[1000 tdm/yr]** | **3.130** | **8.695** | **5.660** | **5.656** | **7.476** |
| **Bioenergy total** | **[EJ/yr]** | **58** | **161** | **105** | **105** | **138** |
| Grazing intensity | [%] | 26% | 11% | 21% | 20% | 17% |

Remember that the bioenergy calculation on cropland and grazing land was assumed to be equal to the annual aboveground plant production (aNPP) in the year 2000 on grazing land, and equal to the potential aboveground NPP of the year 2000 on cropland (for explanation see section ‘Calculation of bioenergy potentials‘). This means that we here give an estimate of the total primary (gross) amount of biomass that can be produced for energy supply. Any ‘downstream’ losses must be deducted. These losses are small if the whole plant can be used directly, without processing, e.g. if grasses, straw or other plant material are burned as solid biofuels in heating furnaces or cogeneration plants. Considerable losses must be taken into account if the biomass is converted to other fuels, e.g. to liquid biofuels. In particular, if it is not possible to use the whole plant – only the edible parts of cereals, rape or soybeans can be converted into first generation liquid biofuels, which means that a large proportion of the plant cannot be used as energy source – then the potential of these areas to supply bioenergy is considerably lower, perhaps amounting to only 25-40% of the values given in Table 13. Residues can only be used for direct combustion as solid biomass or for biogas production (which also entails losses) or for second generation biofuel technologies that still have to be developed (which is, however, generally expected to be the case until 2050).

Note also that we estimate that around 10-25 EJ/yr of bioenergy were also derived from cropland and grazing areas in the year 2000. This estimate would have to be deducted from the values given in the line ‘Bioenergy total’ in order to calculate the *additional* bioenergy potential from cropland and grazing areas in 2050.

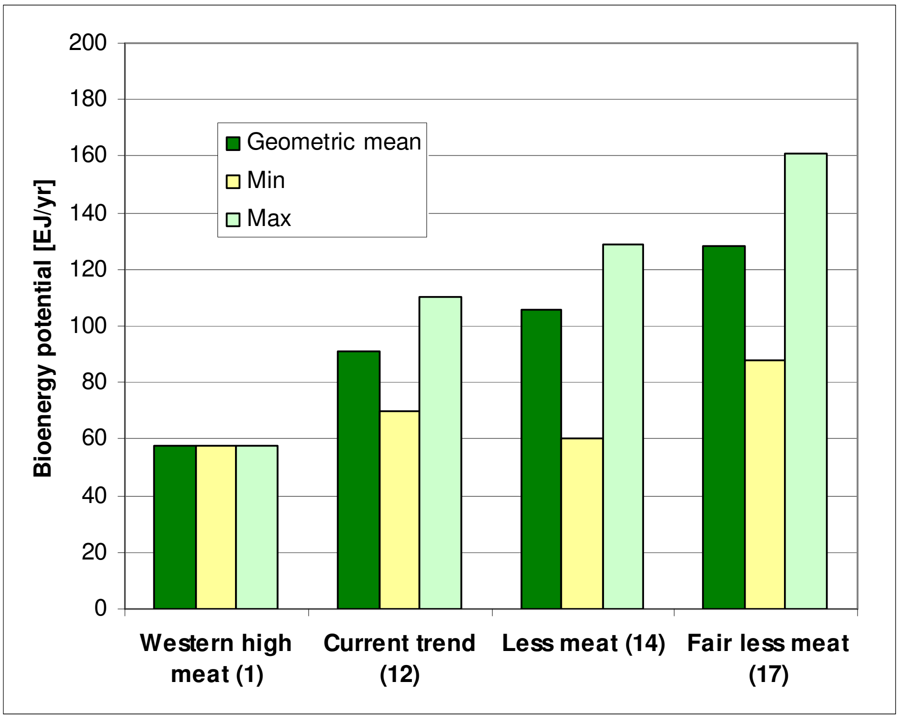

**Figure 16. Dependency of the gross bioenergy potential on assumptions on diets.**
Numbers in brackets indicate the number of scenarios classified as 'feasible' or 'probably feasible for each diet'. 'Min' and 'max' represent the lowest respectively highest bioenergy potential found among these scenarios, the green bar represents the arithmetic mean of these scenarios.

Figure 16 shows that diets exert the strongest effect on the total bioenergy potential. It shows the geometric mean of all 'feasible' and 'probably feasible' scenarios plus the minimum and maximum level of all scenarios with each of the diets. Numbers in brackets are the number of '(probably) feasible' scenario for each diet. The low consumption of animal products in the 'fair less meat' diet allows production of substantial amounts of bioenergy, even if organic agriculture is adopted, due to the very low grazing intensity and the low demand for cropland residues of the livestock sector. This even holds if there is no spare cropland available or even a small 'negative' potential for bioenergy from cropland as in the wholly organic scenario. In contrast, in the case of the 'western high meat diet, the high consumption of animal products implies a high grazing intensity and low free residue potential.

If current trends with respect to diet continue and the FAO assumption on cropland expansion is used, the bioenergy potential is estimated at 105 EJ/yr in the case of strong intensification ('FAO intensive' yields, 'intensive' livestock rearing), 86 EJ/yr in the case of 'intermediate' yields and 'intensive' livestock rearing and 79 EJ/yr in the case of 'intermediate' yields and 'humane' livestock rearing. This difference of 24 EJ/yr amounts to approximately 5% of current global primary energy consumption, undoubtedly a significant amount of energy, but in our view hardly enough to justify a strategy of maximizing yields and efficiencies in the livestock system regardless of the environmental costs or of the amount of animal suffering that might be required to gain it.

## Possible impacts of climate change

The analysis also included an examination of the possible effects of climate change on the feasibility of the different scenarios. As discussed above, the effect of climate change on cropland production is highly uncertain. Therefore, the results of the LPJmL model run on the overall effect of climate change on cropland yields, taking the possible $CO_2$ fertilization effect into account or not (Table 10), was combined with the yield assumptions described above (see Figure 2 and Figure 3). The modified yields were used in the scenario analysis for all 72 scenarios. Table 14 displays the result of this assessment.

The analysis summarized in Table 14 reveals that possible effects of climate change are considerable and that assumptions on the effects and strength of the $CO_2$ fertilization effect[15] are crucial. Whereas the analysis based on the assumption that the fertilization effect is significant yields a considerable enhanced feasibility space (only 10 scenarios of 72 would not be feasible). In this case, the richest diet even becomes ‘probably feasible’ with intermediate yields and BAU cropland expansion; it might even be feasible to achieve such a diet with humane or organic livestock rearing conditions. A ‘wholly organic’ scenario could even deliver a ‘current trend’ diet (‘probably feasible’) and certainly a ‘less meat’ diet.

Quite the opposite happens if the $CO_2$ fertilization effect should fail to kick in. In this case, the ‘current trend’ diet can only be provided with massive land use change if intermediate yield levels are assumed (except in the intensive livestock scenario), and it only enters the ‘feasible’ category in the case of massive land-use change and the most intensive (FAO-predicted) yields on cropland. Diets with less meat remain feasible, but no ‘wholly organic’ scenario seems to be viable under those conditions.

Note, however, that this is a very rough examination of the possible effects of climate change on the agricultural system. First, the modelling of climate change impacts on agro-ecosystems with vegetation / ecosystem models such as LPJmL is in its infancy, so there is a lot of uncertainty here. Second, not all of the combinations examined in Table 14 might actually appear reasonable. For example, it is mostly assumed that the ability to harness the $CO_2$ fertilization effect depends on the availability of other inputs such as water and fertilizer. In other words, due to our modelling strategy we were not able to take possible feedbacks between climate impacts and the biomass flows in the agricultural system into account. We therefore conclude that the results displayed in Table 14 should only taken as a very rough evidence that climate change might have a significant impact on the feasibility/infeasibility of achieving certain diet levels with a given level of agricultural investments and with the respective levels and kinds of agricultural technology and practices.

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[15] Plants take up $CO_2$ from the atmosphere in photosynthesis. Under certain circumstances, a higher $CO_2$ concentration in the atmosphere may promote plant growth (‘$CO_2$ fertilization’). For explanation see footnote 10 and section ‘Taking climate-change impacts into account – possible orders of magnitude‘.

**Table 14. Feasibility analysis of scenarios under climate change, part (A) with, part B without $CO_2$ fertilization effect. For a description, see table 12, for details see text.**

| **(A)** | **Crop yields** | FAO intensive | FAO intensive | Intermediate | Intermediate | Wholly organic | Wholly organic |
|---|---|---|---|---|---|---|---|
| | **Land use change** | Massive | BAU | Massive | BAU | Massive | BAU |
| **DIET** | **Livestock System** | - | - | - | - | - | - |
| Western high meat | intensive | + | +/- | +/- | +/- | - | - |
| Western high meat | humane | +/- | +/- | +/- | - | - | - |
| Western high meat | organic | +/- | +/- | +/- | - | - | - |
| Current trend | intensive | ++ | + | + | + | +/- | +/- |
| Current trend | humane | ++ | + | + | + | +/- | - |
| Current trend | organic | + | + | + | + | +/- | - |
| Less meat | intensive | ++ | ++ | ++ | + | + | +/- |
| Less meat | humane | ++ | ++ | ++ | + | + | +/- |
| Less meat | organic | ++ | ++ | ++ | + | + | +/- |
| Fair less meat | intensive | ++ | ++ | ++ | ++ | ++ | + |
| Fair less meat | humane | ++ | ++ | ++ | ++ | ++ | + |
| Fair less meat | organic | ++ | ++ | ++ | ++ | ++ | + |

| **(B)** | **Crop yields** | FAO intensive | FAO intensive | Intermediate | Intermediate | Wholly organic | Wholly organic |
|---|---|---|---|---|---|---|---|
| | **Land use change** | Massive | BAU | Massive | BAU | Massive | BAU |
| **DIET** | **Livestock System** | - | - | - | - | - | - |
| Western high meat | intensive | - | - | - | - | - | - |
| Western high meat | humane | - | - | - | - | - | - |
| Western high meat | organic | - | - | - | - | - | - |
| Current trend | intensive | + | +/- | +/- | +/- | - | - |
| Current trend | humane | + | +/- | +/- | - | - | - |
| Current trend | organic | +/- | +/- | +/- | - | - | - |
| Less meat | intensive | + | + | + | +/- | - | - |
| Less meat | humane | + | + | + | +/- | - | - |
| Less meat | organic | + | + | + | +/- | - | - |
| Fair less meat | intensive | + | + | + | + | - | - |
| Fair less meat | humane | + | + | + | + | - | - |
| Fair less meat | organic | + | + | + | + | - | - |

# Discussion

## Feasibility analysis

Our feasibility analysis is based on the assumption that cropland expansion as well as expansion of urban and infrastructure areas until 2050 occurs on grazing areas, while we do not assume deforestation. As explained in section ‘Methods and data‘ above, we explicitly check the ability of (reduced) grazing areas to supply sufficient roughage to feed the livestock in each of the scenarios and did not find grazing areas to be limiting in any of our scenario calculations. Any possible future extent of deforestation would therefore not affect our feasibility analysis. The ‘no deforestation’ assumption can be interpreted as being conservative: It means that each ‘feasible’ scenario is possible without any further deforestation until 2050. The classification of a scenario as ‘non feasible’ is solely based on lacking cropland areas, not on lacking grazing areas (it was ascertained that the grazing land was able to deliver the required amount of roughage). A scenario might in theory become feasible if cropland were expanded by more than 19% (our ‘massive expansion’ scenario). In that case grazing areas might become limiting in the absence of deforestation, and then assumptions on deforestation might become relevant in classifying scenarios as feasible/non-feasible. Judging to what extent that might be relevant is outside the scope of this study, but clearly such scenarios would require massive changes in land use and might have major detrimental ecological impacts.

The study shows, however, that deforestation is not required to adequately feed the world population under a wide range of assumptions on future yields, feeding efficiencies, cropland expansion, and diets.

We make the ‘no deforestation’ assumption for reasons of simplification. This should, however, not be misinterpreted. We are aware that tropical deforestation is likely to continue and that agricultural expansion and the promotion of bioenergy are potentially strong drivers of that process. There are good reasons why tropical deforestation rates should be minimized (biodiversity loss, GHG emissions), and this study does not suggest that minimizing tropical deforestation could be achieved without robust policy measures counteracting ongoing trends.

Our analysis suggests that feeding a world with 9.2 billion inhabitants entirely with organic crops and an organic livestock system is probably feasible. Such a scenario would require a growth in global cropland area by approximately 20% until 2050 as compared to the level in the year 2000. It would deliver a diet that is nutritionally sufficient in terms of both nutritional energy (2 800 kcal/cap/day; that is, approximately the level in the year 2000) and protein as well as fat supply. However, the diet would be very low in animal protein, with only 20% of proteins coming from animal products. An egalitarian distribution of food between people is modelled in order to avoid malnourishment. An assessment of the possibility to achieve both of these requirements (diet level/quality and fair distribution) is beyond the scope of this study, but the data we have analyzed give a clear signal that this would require a major departure from both past trajectories and current worldwide patterns. We are sceptical that a change of such proportions could be achieved through conventional measures of environmental / sustainability policy and tend to believe that such a major shift could perhaps only be achieved through a major transformation of society: a sociometabolic transition towards sustainability (Fischer-Kowalski and Haberl, 2007, Fischer-Kowalski and Rotmans, 2009, Haberl et al., 2009, Krausmann et al., 2008b).

A ‘wholly organic’ scenario would probably be very favourable in terms of its environmental and biodiversity impacts, given that most researchers agree that organic agriculture is considerably more biodiversity-friendly than industrialised agricultural practices. Due to the very low level of animal products eaten it would allow to produce a considerable amount of bioenergy of 109 EJ/yr. Note that these conclusions are based on our current assessment that system-wide yield levels of organic agriculture are considerably lower than those of industrialised agriculture due to the need for intercropping / crop rotation as a means to maintain soil fertility. We do not rule out that a targeted effort of agricultural research and development aimed at increasing yields of organic agriculture might succeed in raising yield levels and could allow providing richer diets in a fully organic scenario. For example, if yields could be raised to the 'intermediate' scenario described below, organic agriculture might succeed in providing much richer diets than assumed here.

At the other extreme, we tested the feasibility of providing a world with 9.2 billion inhabitants with a really rich diet. Our calculations suggest that this scenario is 'probably feasible', but only if we assume the highest yield levels ('FAO intensive' yields), massive cropland expansion (again approximately +20%) and an intensive livestock rearing system. The FAO basically assumes that the growth in yields achieved in the last couple of decades will more or less continue linearly over the whole time period until 2050. In some regions, in particular Western Europe and North America, the FAO assumes stunningly, and perhaps unrealistically, high yields. Whether it will be possible to achieve such gains in yields remains to be seen. Biologists tend to be sceptical (e.g., Cassman, 1999; Peng et al., 2000, see also IAASTD, 2009) and it is clear that substantial investments would be indispensable for maintaining growth in crop yields (Kahn et al., 2009), if this is at all possible despite threats such as soil erosion or limits to water supply.[16] Our calculations show, in any case, that such a scenario requires the implementation of every possible option to boost yields and efficiencies in the livestock system. Constraints due to environmental objectives or animal welfare considerations are highly unlikely to be given adequate consideration if such a scenario should be pursued. We find that this scenario also results in the lowest bioenergy potential on cropland and grazing areas found in all scenarios (58 EJ/yr).

Between these extremes there is a whole range of possible options that we classified as 'feasible' or 'probably feasible' according to our biomass balance model. Providing a 'current trend' diet (very similar to the diet level assumed by the FAO for 2050) seems feasible even if 'FAO intensive' projections on crop yields should not become a reality. This diet occurs if past trajectories are extrapolated into the future. It would allow for a considerable improvement of global food supply in terms of both quantity and quality. The level of food supply would allow reducing but not eradicating malnourishment if current patterns of inequality of food supply would remain the same. It would be sufficient to eradicate malnourishment if inequality would be eliminated or at least strongly reduced. Our calculations suggest that 'intermediate' crop yield levels would certainly be sufficient if we assume massive cropland expansion (+19%) and probably sufficient even in the case of business as usua' cropland expansion. Providing the 'current trend' diet would be feasible with humane or organic livestock rearing systems, even in the case of intermediate yield levels. Our calculations suggest that with BAU cropland expansion and intermediate cropland yields, a 'current trend' diet is 'probably' feasible with all three livestock rearing systems. They show that a 'current trend' diet is clearly feasible with intermediate yields if combined with massive cropland expansions, except in the case of organic livestock rearing systems (these are only 'probably feasible'). This shows that humane or even organic standards in livestock rearing are compatible with strong future improvements of diets even if it should be impossible to reach the very high yield levels forecast by the FAO, and even more so if they would be achieved. Claims that the adoption of humane or organic standards of livestock rearing would have a significant detrimental impact on food security are therefore not supported by our results.

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[16] Unambiguous evidence that genetic engineering will be able to ascertain such high yield levels is also still lacking (IAASTD, 2009).

Food security should not be used as an argument against humane or organic livestock rearing systems that provide livestock freedom to roam and significantly reduce animal suffering in livestock production.

That intermediate yields would be sufficient to provide ‘current trend’ diets is good news because these lower yield levels should allow for considerably more environmentally friendly production systems. The intermediate yield assumption can be interpreted as one in which 50% of the area is managed according to organic agricultural standards and 50% according to the FAO intensive assumptions. Alternatively one might assume that the whole agricultural sector would place a higher emphasis on environmental considerations and forego some options to boost yields in order to protect the environment. Such scenarios might still allow the production of considerable amounts of bioenergy. The difference in the bioenergy potential of the ‘current trend’ diet scenario with FAO intensive crop yields and intensive livestock rearing (103 EJ/yr) and a ‘current trend’ diet scenario with intermediate yields and humane livestock rearing (79 EJ/yr is only 24 EJ/yr or about 5% of current global primary energy use – an amount of energy that would hardly justify to boost yields and efficiencies in the livestock system regardless of environmental costs and the amount of animal suffering entailed.[17] Of course environmental impacts may be further reduced and / or bioenergy potential increased if people were to adopt a diet according to our ‘less meat’ assumptions. Under these assumptions, the level of calorie intake would be identical to that in the ‘current trend’ scenario but the contribution of animal products to total protein supply would decrease from 38% to 30% in the global average.

## Possible impacts of climate change

The extent to which climate change might change the picture is difficult to evaluate at present. Simulations of the climate impacts on yield levels reveal a considerable level of uncertainty. We here demonstrate the range of possible impacts by reporting on simulations of cropland yields derived from model runs with the dynamic global vegetation model (DGVM) LPJmL. This model is a process based simulation tool that calculates plant growth depending on climate (precipitation, temperature, atmospheric $CO_2$ concentration) and soil conditions. It provides a comprehensive picture of global carbon and water flows and includes a crop module that was used to estimate the potential impacts of climate change on global cropland yields in 2050. The average percent changes of cropland yields in each of the regions considered in this study were applied to the forecast crop yields in the FAO intensive, intermediate and wholly organic scenarios and then fed into the biomass balance model. The results suggest that climate change might result in increases or decreases of cropland yields, depending on the extent to which a possible $CO_2$ fertilization effect actually affects cropland yields. Not surprisingly, our calculations suggest that the feasibility of a certain combination of assumptions on yields, diets, cropland expansion and feeding efficiencies in the livestock system is strongly affected by the climate change impact, and that increases in yields positively affect the feasibility of the scenarios studied here. However, this model system was not capable of fully considering possible feedbacks between management and climate impact, even though we are aware that such feedbacks might be highly relevant. So we conclude that the possible

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[17] Note that a full appreciation of all factors that determine whether a particular bioenergy or biofuel technology may be classified as being sustainable is beyond the scope of this study. Among others, this would require considerations on GHG emissions, energy return on investment (EROI), fertilizer and pesticide use, water availability, etc. Evaluating such issues is only possible when referring to specific bioenergy utilization pathways and technologies, which is also beyond the scope of this report.

impact of climate change may be substantial but is still highly uncertain. It is encouraging, though, that our calculations indicate that the global agricultural system would probably be able to deliver the ‘current trend’ diet with intermediate yield levels even if we assume a negative impact of climate change on yields.

## The relative importance of changes in diet, cropland area, yields and productivity of the livestock system

Our analysis suggests that the demand for food, both in absolute amounts and the fraction of animal products, as well as assumptions on achievable yields in 2050 are decisive for the question whether it will be possible to ‘feed and fuel the world sustainably, fairly and humanely’. The amount of land available for cropland expansion is also an important factor, whereas the analysis showed that differences in the overall feeding efficiencies (referring to the input-output ratio of the livestock systems) and area demand of the different livestock systems (intensive, humane and organic) have a smaller influence on the overall result than the other factors. This is due to the fact that our review of the literature suggested relatively modest differences in feeding efficiencies between intensive, humane and organic indoor-housed livestock rearing (10-20%). This is relatively low, especially when compared to the much larger differences in feeding efficiencies between extensive and optimised systems (of any kind) and even more so between subsistence and optimised systems. Moreover, remember that we assume that subsistence and extensive market-integrated livestock rearing, characterized by low outputs per unit of input, will both still play a considerable role in 2050, and that we did not modify the share of extensive and subsistence farming in the different scenarios. The choice between organic, humane or intensive livestock rearing only affected livestock assumed to be kept in optimised systems in 2050, but not the share of subsistence and market-oriented extensive systems.

It should be noted at this point that extensive livestock systems with low outputs per unit of input are not necessarily inefficient. The efficiency measure (input-output ratio) is based on the tacit assumption that animal protein is the major output of livestock systems, a perspective which may be adequate for livestock production in industrialised countries, but which fails to account for the utility of livestock in less developed regions and severely distorts the comparative picture (see Bradford and Baldwin, 2003): Besides meat and milk production, livestock fulfils a huge range of other functions. In many regions livestock is required to provide power for agriculture and transport. In developing regions, between 20 and 35% of total feed demand originates from animals primarily used to provide draft power (Krausmann et al., 2008a). In low-input agriculture, livestock is essential for the management of nutrients, allowing for efficient transfers and conversion of plant nutrients. A crucial function of livestock is the ability of ruminants to convert biomass not digestible by humans into food for humans, for example, biomass from waste lands or semi-deserts. Thus, livestock systems that appear to be inefficient due to their input-output ratio may in fact represent well-adapted, highly efficient production systems in their respective local contexts.

The feasibility analysis also indicates that the additional costs of humane and organic livestock rearing systems in terms of feeding efficiency and demand for additional area seem to be relatively low: Differences in the livestock systems assumed in the scenarios played only a minor role in determining whether a scenario was feasible or not. However, the study also shows that the data uncertainties and the current limited scientific understanding do not allow for unambiguous statements with this regard and better information seems highly desirable to draw more robust conclusions on that issue.

## Bioenergy potentials

Estimates of the size of future bioenergy potentials have gained a lot of attention in recent years, in particular because the possibility to continue current growth trajectories of global energy use based mainly on fossil fuels is increasingly seen pessimistic on the grounds of (a) limited supplies, at least of conventional oil and gas ('peak oil', 'peak gas'; Deffeyes, 2001, Hall et al., 2008)[18] and (b) the GHG emissions resulting from a continuation of current trajectories of fossil fuel use (Nakicenovic and Swart, 2000, IPCC, 2007b). Analysts increasingly argue that biomass combustion with consequent carbon capture and storage (abbreviated CCS, see Jaccard, 2005; IPCC, 2007a, Rhodes and Keith, 2008) should be promoted on a grand scale in order to achieve negative GHG emissions. Negative GHG emissions are required to limit global warming until 2100 to 2° Celsius, a goal thought to be required to reduce the risk of catastrophic runaway events as the earth system might reach so-called 'tipping points' (Lenton et al., 2008, Kriegler et al., 2009).

According to this study, the level of bioenergy production from agricultural areas will depend largely on the development of diets and the opportunities and constraints involved in expanding and intensifying the use of land currently used for grazing. Note that, according to the no-deforestation assumption followed in this study, the two cropland expansion scenarios yield similar bioenergy potentials if everything else is assumed to be equal, because cropland expansion is assumed to reduce grazing land. Bioenergy potentials on grazing land, as calculated in this study, are large, but might entail massive investments in agricultural technology, such as irrigation infrastructure, and will most probably be associated with vast social and ecological effects, such as a further pressure on populations practising low-input agriculture. Realising this potential would likely also trigger indirect land use change such as deforestation in far distant regions if not combined with robust measures to prevent such effects (e.g. Searchinger et al., 2008, Fargione et al., 2008, Koh and Ghazoul, 2008).

Table 15 compares the results of this study on global bioenergy potentials (excluding forestry) with the current level of energy use as well as with other studies on global bioenergy potentials. Note that the bioenergy potentials given in this study are not *additional* to the current level of bioenergy use, but include the amount of bioenergy coming from cropland and grazing areas today (as indicated above, this amount is highly uncertain and might amount to 10-25 EJ/yr; the remaining bioenergy used today is assumed to come from forestry).

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[18] Other authors argue that unconventional supplies might overcome shortages of conventional oil and gas or that oil and gas resources are much larger than generally thought (e.g., Jaccard, 2005, Odell, 2004)

**Table 15. Current and projected future level of global biomass and energy use and global terrestrial net primary production: A compilation of estimates.**

| | Energy flow [EJ/yr] | Year | Sources |
|---|---|---|---|
| **1. Current global NPP and its use by humans (gross calorific value)** | | | |
| Total NPP of plants on earth's land | 2 191 | 2000 | [1] |
| Aboveground NPP of plants on earth's land | 1 241 | 2000 | [1] |
| Human harvest of NPP including by-flows, total | 346 | 2000 | [1,2] |
| Human harvest of NPP including by-flows, aboveground | 310 | 2000 | [1,2] |
| NPP harvested and actually used by humans | 225 | 2000 | [1,2] |
| **2. Global human technical energy use (physical energy content)** | | | |
| Fossil fuels (coal, oil, natural gas), gross calorific value | 453 | 2008 | [3] |
| Nuclear heat (assumed efficiency of nuclear plants 33%) | 30 | 2008 | [3] |
| Hydropower (assumed efficiency 100%) | 11 | 2008 | [3] |
| Wind, solar and tidal energy (100% efficiency) | 1 | 2006 | [4] |
| Geothermal (10% efficiency for electricity, 50% for heat) | 2 | 2006 | [4] |
| Biomass, including biogenic wastes, gross calorific value | 54 | 2006 | [4] |
| Total (physical energy content, gross calorific value) | 551 | 2006-2008 | [3,4] |
| **3. Estimates of global bioenergy potentials or scenarios 2050 (calorific value not standardized)** | | | |
| Bioenergy crops and residues, excluding forestry, this study | 58-161 | 2050 | |
| Mid-term potential according to the *World Energy Assessment* | 94-280 | 2050 | [5] |
| Review of mid-term potentials according to Berndes et al. | 35-450 | 2050 | [6] |
| Mid-term potential according to Fischer/Schrattenholzer | 370-450 | 2050 | [7] |
| Potential according to Hoogwijk | 33-1 135 | 2050 | [8] |
| *IPCC-SRES* scenarios mid-term | 52-193 | 2050 | [9] |
| Bioenergy potential on abandoned farmland | 27-41 | 2050 | [10] |
| Bioenergy potentials in forests | 0-71 | 2050 | [11] |
| Surplus agricultural land (not needed for food & feed) | 215-1 272 | 2050 | [12] |
| Bioenergy crops (second generation) | 34-120 | 2050 | [13] |

[1] Haberl et al., 2007
[2] Krausmann et al., 2008a
[3] BP, 2009. BP reports energy data in tons of oil equivalent (toe) net calorific value. We assumed that 1 toe = 41.868 GJ (NCV). Conversion from NCV to gross calorific value (GCV) was based on the following multipliers (GCV/NCV): coal 1.1, oil 1.06, natural gas 1.11 (Haberl et al., 2006).
[4] IEA, 2008. The IEA reports biomass as NCV; we converted this to GCV using a multiplier of 1.1
[5] Turkenburg, 2000.
[6] Berndes et al., 2003
[7] Fischer and Schrattenholzer, 2001
[8] Hoogwijk et al., 2003
[9] Nakicenovic and Swart, 2000
[10] Campbell et al., 2008, Field et al., 2008
[11] Smeets and Faaij, 2007
[12] Smeets et al., 2007
[13] WBGU, 2008

Global technical primary energy use (i.e. exclusive of the biomass used for food, feed and fibres, see Haberl, 2001) is currently approximately 551 EJ/yr. 82% of this energy (453 EJ/yr gross calorific value) is currently derived from coal, oil and natural gas, approximately 10% from biomass and the remainder from nuclear energy, hydropower, wind, solar and geothermal energy.

Our results suggest that the amount of *additional* primary biomass energy from cropland and grazing areas is between 33 and 151 EJ/yr (these numbers result from subtracting 10-25 EJ/yr from the total potentials identified in our calculations). Future diets play an enormous role in influencing the size of this potential: Rich diets result in low bioenergy potentials, while significantly higher bioenergy potentials might be realistic in the case of diets with a lower share of animal products. If we assume intermediate crop yields, ‘current trend’ diet and humane livestock rearing – a plausible scenario in terms of diets and a moderate one in terms of crop yields and feeding efficiencies – the additional bioenergy potential from cropland, residues and grazing areas might be around 60 EJ/yr, i.e. 13% of current fossil energy supply. This means that biomass energy, where produced sustainably, could play a significant role for future energy supply, but it is certainly not a ‘silver bullet’ to solve all, or even most, of humanity’s energy problems in the face of climate change.

Figure 17 distinguishes between two different parts of the bioenergy potential: ‘primary biomass’ refers to bioenergy crops grown on cropland or grazing areas; ‘residues’ refers to agricultural residues on cropland that are not required in the livestock system or for the maintenance of soil fertility. It shows that a considerable amount of bioenergy (21-36 EJ/yr or 18-52% of the total bioenergy potential) is available through the ‘cascade’ use of cropland residues. This biomass fraction is a vital component of the functioning of agro-ecosystems and is important for the maintenance of soil fertility (Lal, 2005). Strategies aimed at fostering its usage should therefore be viewed cautiously. Nevertheless, our calculations reveal that this is a significant potential, which renders in-depth assessments of options to combine bioenergy production and soil fertility management (e.g., energy production through biogas production that maintains a large proportion of the nutrients and parts of the carbon) promising. Furthermore, such investigation should probably be prioritized, as the use of cascade biomass (Haberl and Geissler, 2000, Haberl et al., 2003, WBGU, 2008) entails no or limited further pressures on ecosystems.

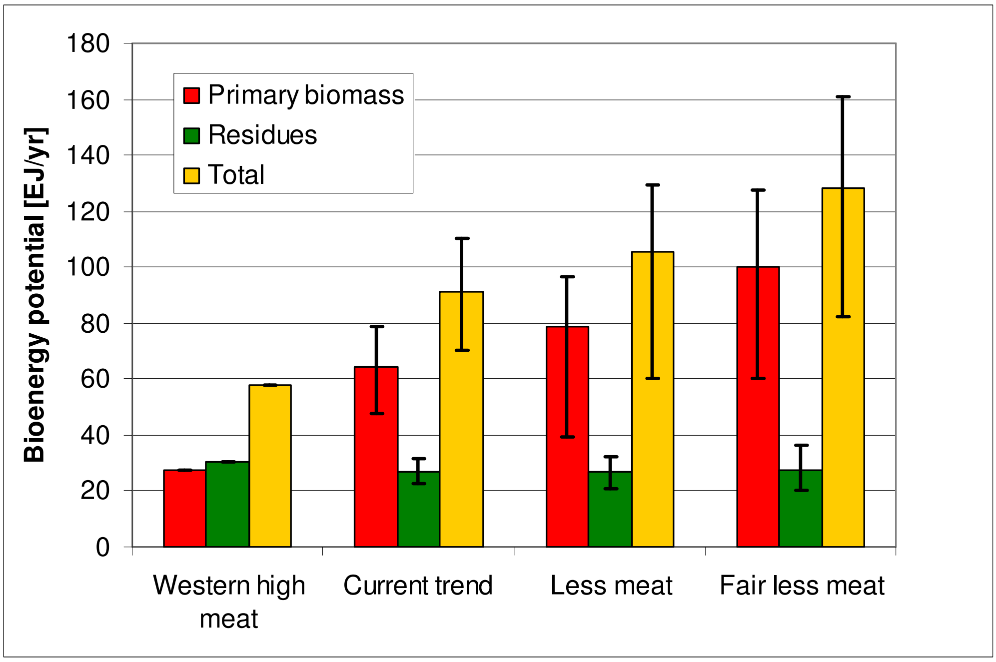

**Figure 17. Analysis of the bioenergy potentials from residues and primary biomass**

‘Primary biomass’ is the sum of the bioenergy crop potentials on cropland and on grazing areas. ‘Residues’ refers to the bioenergy potential from residues on cropland.

Our study underlines that assumptions on diets and agricultural production technologies have massive effects on the availability of future bioenergy potentials, in particular with respect to the primary biomass potential which is much more variable than the residue potential: the primary biomass potential ranges from 28 EJ/yr in the ‘western high meat’ diet scenario to

128 EJ/yr in a scenario with the unlikely combination of a 'fair less meat' diet with FAO intensive crop yields and intensive livestock production. Note that the range of values for the primary bioenergy crop potential we find (28-128 EJ/yr) is almost identical to that identified by the WBGU (2008) – their results ranged from 34 to 120 EJ/yr (Table 15) –, even though the WBGU calculations were based on an entirely different methodology.[19] Our results suggest, in any case, that bioenergy potential calculations which do not take interlinkages into account are almost meaningless. Moreover, vital and decisive uncertainties related to the effects of climate change make assumptions on future agricultural productions highly uncertain.

Our results suggests that, depending on the assumptions on diet, livestock system, yields and land-use change, total bioenergy potentials from farmland (including the amount of bioenergy currently produced on these lands) may range from 58 to 161 EJ/yr. Compared with other estimates in the literature (Table 15), we conclude that our estimate is at the lower range of the spectrum. Bioenergy potentials from farmland in the year 2050 above 200 EJ/yr seem hardly conceivable in the light of the present results.

The lowest bioenergy potential is found in the scenario with the richest diet. The highest potentials were found in scenarios in which the lowest diet ('fair less meat') was combined with highly intensive cropland and livestock rearing – a combination of factors that can be assumed to be highly improbable. Realistic values might be in the range of 70-100 EJ/yr, an order of magnitude that can be achieved with the 'current trend' diet and even with intermediate yield levels and humane animal rearing systems.

Note that all bioenergy figures given here refer to the gross potential to provide biomass for energy generation and assume that the entire aboveground compartment of bioenergy crops can be used to produce energy (i.e. use of the whole plant, no large conversion losses). This is reasonable if one assumes direct combustion of solid biomass, but not if biomass is transformed to liquid biofuels, in particular first generation biofuels. The potential to produce first generation biofuels is considerably lower, also due to the fact that residues from cropland account for a large fraction of the total bioenergy potential in most scenarios. This does not imply a step back towards environmentally destructive 'traditional' biomass technologies that have tremendously detrimental health effects: Modern biomass furnaces, in particular if used in cogeneration plants, could meet high emission standards and have a high efficiency in terms of both enthalpy and exergy (combined production of power and heat).

## Land-use intensity

The scenarios differ not only with regard to their bioenergy potential, but also with regard to the level of environmental pressure exerted on the world's terrestrial ecosystems. A full assessment of these pressures was beyond the scope of this study. However, one output of our calculations – i.e. grazing intensity – can give some indication of the amount of environmental pressure associated with each scenario, as discussed in this section.

One of the most obvious differences of the scenarios analyzed here relates to the amount of biomass harvested on grazing areas to feed the livestock required for each diet (given a certain level of feed supply from cropland that depends on cropland yields). Grazing intensity is defined as the ratio between biomass harvested on grazing areas to the amount of annual

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[19] The WBGU used the LPJmL dynamic global vegetation model to estimate the bioenergy crop potential on areas with herbaceous vegetation cover. Their calculations entailed a series of restrictions in area availability (e.g., protected areas were excluded or additional area required for food production was considered).

aboveground biomass production ($aNPP_{act}$) on grazing areas yields the indicator grazing intensity. The grazing intensity in each scenario is reported in Table A 13 in the Annex (last column).

Figure 18 shows that grazing intensity is significantly different between the four diet scenarios (left, blue columns) if it is not assumed that the bioenergy potential on grazing areas will be actually realized. The only feasible 'western high meat' scenario, characterized by high calorie intake and an elevated consumption of animal products, is associated with a grazing intensity of 26%. In contrast, the scenarios of the 'fair less meat' diet group result in an average grazing intensity of 14%, within a range between 11% and 17%, or about half of the environmental pressure on the global grazing areas of the 'western high meat' scenario.

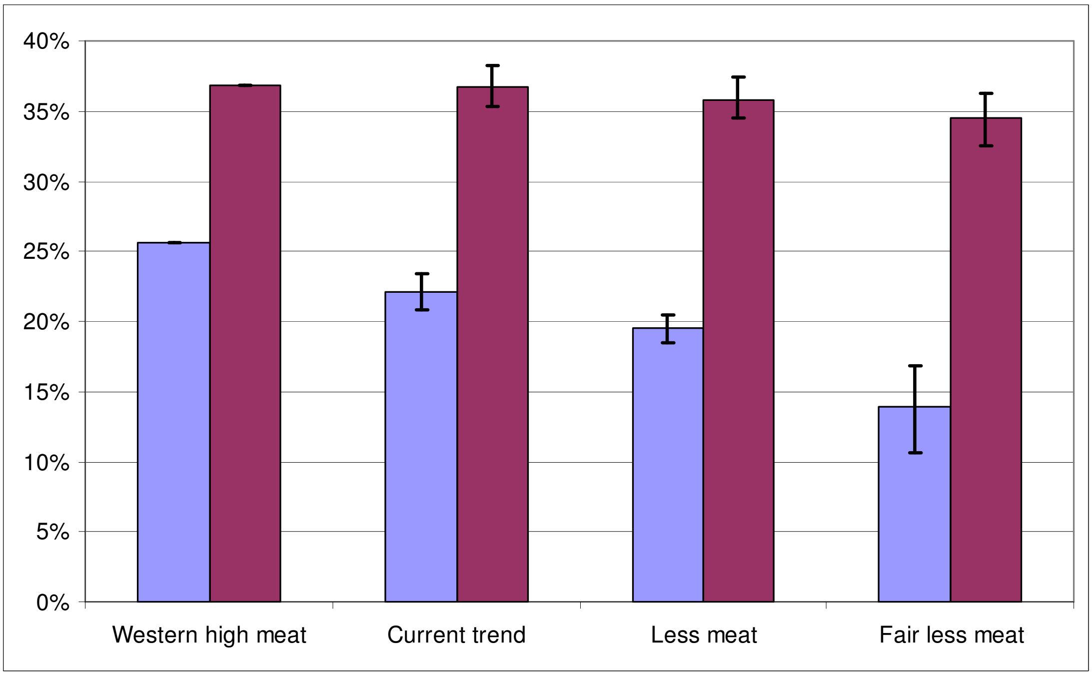

**Figure 18. NPP harvested as percentage of aboveground $NPP_{act}$ on grazing areas: the left (blue) bars indicate grazed biomass, the right (purple) bars indicate grazed biomass plus biomass produced for energy supply on grazing areas.**

The differences between the scenarios are less pronounced when calculating land use intensity resulting from the sum of bioenergy potential and grazed biomass on current grazing areas in the year 2050 (Figure 18, right, purple columns). These purple columns are calculated assuming that grazing areas do not only supply the amount of feed required in each scenario, but that the full extent of the bioenergy potential on grazing areas assumed to exist in each scenario is also realized and the respective amount of biomass is harvested for bioenergy production. In calculating the bioenergy potentials, we assume that grazing intensity in the grazing areas of class 1 (highest grazing suitability) is increased to a maximum level (exploitation rate of 67% of the actual aboveground NPP for developing and 75% for industrialised regions), and actual NPP of the grazing area set free through that amount of intensification is then assumed to be available for bioenergy production. The scenarios differ due to different grazing intensities in the classes 2 to 4. Land-use intensity of grazing land of the quality 1, in consequence of these assumptions, is a mixture of exploitation rates of 67% (grazing in developing countries), 75% (grazing in industrialised countries) and 100% (residual bioenergy potential) of aboveground actual NPP. All four diet scenarios are characterized by a land-use intensity on grazing areas of around 35%. This is a considerable surge when compared to the current intensity of grazing land use, which was 19% in the year 2000 (Haberl et al., 2007). We take this as an indication that the realization of the bioenergy potentials identified in this study, in particular of the bioenergy potentials that depend on bioenergy crops grown on cropland or grazing areas, might have significant environmental impacts that should be well considered before actually embarking on a large-scale realisation of these potentials.

Grazing intensity is directly and indirectly linked to the condition of grazed ecosystems, their nutrient cycling ability and the intactness of ecosystem functioning. Increased grazing intensity may result in changes in soils such as decreased fertility, top-soil losses, reduced water holding capacity and decreased infiltration (Asner et al., 2004, Harris, 2000). In general, grazers influence ecosystems by removing biomass, often in substantial amounts, and mostly in a selective way; thereby altering species composition (Diaz et al., 2007, Skarpe, 1991). Furthermore, grazing can be associated with negative impacts such s soil compaction, trampling, concentration of nutrients, defoliation (sometimes to an extent that can limit the productive capacity of grazed ecosystems), alter carbon and nutrient flows and can influence soil quality, ecosystem nutrient status, and finally forage production (Asner et al., 2004, Conant, 2002, Ferraro and Oesterheld, 2002, Milchunas and Lauenroth, 1993, Skarpe, 1991).

Grazing does not necessarily have such negative impacts, however, because biomass removals can under certain circumstances be partly or even fully compensated by enhanced plant growth, in particular at low or intermediate levels of grazing intensity (Harris, 2000). Continued overgrazing, however, i.e. holding grazing intensity and/or frequency above the limits of vegetation and soil recovery for longer periods, will usually result in soil and vegetation degradation. Degradation has been defined as a persistent decrease in the productive potential of the (grazed) ecosystems (Oldeman, 1988, Safriel et al., 2005). In general, intensive levels of grazing are often associated with overall negative environmental effects (Biondini et al., 1998, Detling, 1988, Skarpe, 1991), although the extent and severity of such negative effects depends on management and can sometimes be mitigated through appropriate management methods (see below). In addition, grazing often is accompanied by problematic measures such as fencing and fragmentation of habitats, eradication of ‘problematic’ wild animals, the introduction of exotic plants, reductions in numbers of non-domesticated ungulates, and alterations of fire regimes, with far reaching consequences for ecosystem functioning (Freilich et al., 2003, White et al., 2000). Furthermore, large-scale increases of land use intensity on grazing areas are likely to be related to social conflicts, such as competition for forage, land tenure disputes, or pressures on populations practicing subsistence agriculture (Conant, 2002).

However, intensification of grazing areas does not inevitably result in overgrazing or widespread degradation. Even severe forms of degradation can be mitigated, for example by fertilization, irrigation, or management techniques that help to conserve the soil and restore grazing ecosystems (Blaikie and Brookfield, 1987, Daily, 1995). Such measures of intensification would usually entail substantial, sometimes even massive investments in agricultural technology, in particular irrigation infrastructure and fertilization, in order to prevent soil and vegetation degradation (Harris, 2000, Turner et al., 2005).

# Conclusions and policy recommendations

## Diets

**Conclusion:** Our findings strongly underline the view that the share of animal products in human diets has a strong effect on environmental impact, the possibility to produce animal products humanely or through organic livestock rearing.

**Recommendation:** Any effective measures to reduce the level of consumption of animal products (including those derived from eggs and milk) are beneficial in terms of environmental impacts, animal welfare, biodiversity, and bioenergy potential.

## Organic agriculture

**Conclusion:** We provide evidence that organic agriculture can probably feed a world population of 9.2 billion in 2050, if relatively modest diets are adopted, where a low level of inequality in food distribution is required in order to avoid malnutrition. This conclusion is based on the best currently available data on system-wide yield levels of organic cropland agriculture as compared to intensive crop production systems. If agricultural research were to succeed in developing higher-yielding variants of organic agriculture, richer diets based on organic agriculture could be achieved. Judging to what extent this is feasible is beyond the scope of this study. We clearly show that the extent to which foreseen diet trajectories have to be modified towards less rich diets strongly depends on the ability to reach higher yields in organic or environmentally less demanding agriculture.

**Recommendation:** We therefore recommend to direct research and technical development towards agricultural practices that follow organic standards or are otherwise environmentally less destructive and are nevertheless able to achieve high yield levels.

## Humane and environmentally friendly farming

**Conclusion:** We provide strong evidence that neither humane livestock rearing systems nor environmental objectives in cropland farming should be discarded based on claims that these practices would jeopardize food security. To the contrary, we did not find a strong effect on the feasibility of scenarios of feeding efficiencies and the additional area demand of free-range systems for monogastric species associated with humane or even organic livestock rearing standards. While a transition to wholly organic cropland agriculture (100% of the area planted according to organic standards) seems to be challenging in terms of the changes in diets and the need for an equitable distribution of food in such a scenario, we find that even the intermediate yield scenario (that might, for example, be achieved by organic agriculture on 50% of the area, if the other 50% were as intensively cultivated as foreseen by the FAO) would be able to deliver a ‘current trend’ diet in 2050.

**Recommendation:** We therefore recommend a continuation of support for organic and other environmentally benign agricultural management practices, while at the same time trying to optimize yields and efficiencies without adopting unsustainable or inhumane technologies and practices. Our calculations suggest that there is no need to boost yields and efficiencies regardless of the costs in terms of environmental pressures and animal welfare.

## Bioenergy

**Conclusion:** Expectations with respect to future bioenergy potentials should be lowered to more realistic levels. Our study provides strong evidence that explicit consideration of roughage demand of livestock to be covered on grazing areas has a significant effect on the bioenergy potential in 2050. The range of bioenergy potentials from cropland and grazing land identified here is considerably lower than many studies put forward in the last years. Moreover, we find that future diets have a strong effect on the size of the bioenergy potential. Under 'business-as-usual' assumptions on diets, the bioenergy potential on cropland and grazing land is in the order of magnitude of 100 EJ/yr, including the bioenergy currently produced on these areas.

**Recommendation:** Sustainability issues involved in strategies aiming at a promotion of bioenergy need to be taken seriously. The integrated optimization of food, fibre and bioenergy supply ('cascade utilization of biomass') is an important element of any sustainable bioenergy strategy. Area demand of bioenergy – as well as of all other renewable energies – should be considered highly important when judging the relative merits of different renewable energy (bioenergy) technologies. First generation biofuels perform particularly poorly with respect to that criterion. The combustion of solid biomass in combined heat and power (cogeneration) plants is probably much more favourable in terms of energy efficiency. Environmental issues associated with bioenergy, in particular of dedicated bioenergy crops, should be evaluated carefully before pushing these technologies on a grand scale.

## Need for additional research

More detailed research is required on system-level efficiencies of different livestock rearing systems and *ceteris-paribus* (everything else kept constant) comparisons of cropland yields in industrialised and organic agriculture. While we feel reasonably certain that these uncertainties probably do not affect the main recommendations formulated above, but more research into these issues would be helpful in order to better understand the interrelations and feedbacks in the global food and agriculture system.

A combination of the modelling strategy pursued here (based on calculating consistent biomass balances, i.e. the socioeconomic metabolism approach) could gain a lot if combined or even integrated with traditional methods based on economic modelling and / or ecosystem modelling (e.g. vegetation models). Research in that direction would help to better understand the dynamics of coupled global social-economic-ecological systems that is at the heart of the global sustainability challenge.

# Abbreviations

| | |
|---|---|
| CCS | Carbon capture and storage |
| DGVM | Dynamic global vegetation model |
| DEFRA | Department for Environment, Food and Rural Affairs (UK government) |
| FAO | Food and Agriculture Organization of the United Nations |
| FRA | Forest resource assessment (FAO) |
| GAEZ | Global Agro-Ecological Zones (FAO/IIASA) |
| GDP | Gross domestic product |
| GHG | Greenhouse gas |
| GLP | Global land project, www.globallandproject.org |
| HANPP | Human appropriation of net primary production |
| IAASTD | Intl. Assessment of Agricult. Knowledge, Sci. & Technology for Development |
| IEA | International Energy Agency |
| IFOAM | International Federation of Organic Agriculture Movements |
| IIASA | International Institute of Applied Systems Analysis (Laxenburg, Austria) |
| IPCC | Intergovernmental Panel on Climate Change |
| LPJmL | Lund-Potsdam-Jena model with managed land (a DGVM) |
| NPP | Net primary production = biomass produced by plants through photosynthesis |
| RTD | Research and technical development |
| TBFRA | Temperate and boreal forest resource assessment (FAO) |
| UN | United Nations |
| WBGU | Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen |

# Units

Land-use data are given in square kilometers ($km^2$). 1 $km^2$ = 1 km x 1 km = 1,000 m x 1,000 m = 1 million $m^2$. 1 $km^2$ = 100 hectares (ha).

Data on biomass flows are given as dry matter and measured in (metric) tons or kg. 1 t = 1,000 kg = 1 million gram (Mg). If not explicitly stated otherwise, biomass flow data were converted from carbon (C) to dry matter assuming a C content of dry matter biomass of 50% and from energy by assuming a gross calorific value (GCV) of dry matter biomass of 18.5 MJ/kg.

Energy is measured in the SI unit Joule (J). 1 Joule = 1 Watt x 1 second = 1 Newton x 1 meter. Other energy units: 1 kWh = 3.6 MJ. 1 kcal = 4.1868 kJ. 1 British Thermal Unit (BTU) = 1.0551 kJ (1 Quad = $10^{15}$ BTU). 1 ton oil equivalent (toe) = 41.868 GJ. 1 t SKE (hard coal equivalent) = 29.3076 GJ. If not explicitly stated otherwise, energy resources were converted to Joules assuming gross calorific values (GCV) that include the energy of the condensation of water vapour in flue gas. Net calorific values are 0-20% lower than GCV for most fuels. Food flows were expressed in kilocalories (kcal) nutritional value. Nutritional values (dietary energy) are lower than GCV.

We use the following prefixes:

| | | | | |
|---|---|---|---|---|
| k | kilo | $10^3$ | | |
| M | Mega | $10^6$ | = | 1 million (mio.) |
| G | Giga | $10^9$ | = | 1 billion (bio.) |
| T | Tera | $10^{12}$ | | |
| P | Peta | $10^{15}$ | | |
| E | Exa | $10^{18}$ | | |

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# Appendix

## Bioenergy potentials in forests

It is well known that harvests in forests are considerably lower globally than global wood increment: The total wood production potential of all forest areas excluding the protected areas has been estimated to be around 112 EJ/yr globally (Smeets and Faaij, 2007). Wood removals from forests according to FAO data were around 36 EJ/yr globally around the year 2000 (Krausmann et al., 2008a). It would be wrong, however, to assume that the difference (76 EJ/yr) would indicate the magnitude of the bioenergy production potential of forests. First, there is evidence that the FAO underestimates wood removals from forests; that is, wood harvests are probably already larger than those included in FAO statistics (Haberl et al., 2007, Krausmann et al., 2008a). Second, it is economically not viable to harvest forests only for fuel wood production. Usually, fuel wood is largely a by-product of roundwood production. Third, economic considerations (e.g., accessibility), social and cultural values (e.g., livelihoods, sacred forests, etc.) and ecological considerations (biodiversity consideration, carbon / greenhouse gas balance) limit the exploitation of forests for energy production. Nevertheless, the above quoted data suggest that forests should be able to maintain or even expand their role as a source of bioenergy until 2050. Evaluating how much bioenergy from forests can be produced sustainably, i.e. in a manner that is ecologically sound, economically viable and socially acceptable is beyond the scope of this report. An influential article concluded that the additional bioenergy potential from forests might range from 0 to 71 EJ/yr in the year 2050, depending on its definition. According to this study (Smeets and Faaij, 2007), the global technical potential for forest bioenergy in 2050 was found to be 64 EJ/yr, the economic potential 15 EJ/yr, the ecological potential 8 EJ/yr and the combined economic-ecological 0 EJ/yr.

# Additional tables

**Table A 1. Definition of regions used in this study**

| | |
|---|---|
| Northern Africa and Western Asia | Algeria, Armenia, Azerbaijan, Cyprus, Egypt, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Libyan Arab Jamah., Morocco, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, Turkey, United Arab Emirates, Western Sahara, Yemen |
| Sub-Saharan Africa | Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Rep., Chad, Dem. Rep. of Congo, Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, United Rep.Tanzania, Togo, Uganda, Zambia, Zimbabwe |
| Central Asia and Russian Federation | Kazakhstan, Kyrgyzstan, Russian Federation, Tajikistan, Turkmenistan, Uzbekistan |
| Eastern Asia | China, Japan, Korea,Dem.Ppl's.Rep., Korea, Republic of, Mongolia |
| Southern Asia | Afghanistan, Bangladesh, Bhutan, India, Iran(Islamic Rep. of), Nepal, Pakistan, Sri Lanka |
| South-Eastern Asia | Papua New Guinea, Brunei Darussalam, Cambodia, Indonesia, Lao People's Dem. Rep., Malaysia, Myanmar, Philippines, Thailand, East Timor, Viet Nam |
| Northern America | Canada, United States |
| Latin America & the Carribean | Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, French Guiana, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Suriname, Trinidad and Tobago, Uruguay, Venezuela |
| Western Europe | Austria, Belgium-Luxembourg*, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom |
| Eastern & South-Eastern Europe | Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, T.F.Yug.Rep. Macedonia, Republic of Moldova, Poland, Romania, Yugoslavia, Slovakia, Slovenia, Ukraine |
| Oceania and Australia | Australia, New Zealand |

* not differentiated.
The regional grouping is based on the classification of the macro geographical (continental) regions and geographical sub-regions as defined by the United Nations Statistical Division (UNSD, 2006).

**Table A 2. Ratios of protein, fat and carbohydrates to total kilocalories, for each food category and region.**

| g/1000 kcal | | N Africa W Asia | Sub-Sah. Africa | C. Asia, Russ. Fed. | E. Asia | S. Asia | S.-E. Asia | N. America | Lat. Am., Carribean | W. Europe | E.&S.E. Europe | Oceania, Australia |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Protein | Cereals | 29 | 25 | 27 | 21 | 24 | 20 | 26 | 24 | 28 | 27 | 28 |
| | Roots | 21 | 10 | 24 | 15 | 18 | 7 | 26 | 16 | 23 | 24 | 24 |
| | Sugar crops | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pulses | 65 | 65 | 67 | 66 | 60 | 63 | 66 | 64 | 65 | 65 | 65 |
| | Oil crops | 4 | 12 | 2 | 20 | 3 | 21 | 5 | 5 | 2 | 2 | 3 |
| | Vegetables, fruits | 26 | 20 | 28 | 42 | 30 | 25 | 23 | 18 | 21 | 26 | 20 |
| | Meat (ruminants) | 81 | 91 | 79 | 92 | 99 | 104 | 123 | 99 | 106 | 97 | 94 |
| | Pigs, poultry, eggs | 81 | 57 | 61 | 41 | 62 | 46 | 64 | 52 | 51 | 48 | 55 |
| | Milk, butter, dairy | 49 | 50 | 50 | 54 | 43 | 55 | 53 | 53 | 49 | 49 | 50 |
| | Fish | 154 | 157 | 150 | 146 | 164 | 160 | 163 | 124 | 133 | 147 | 156 |
| | Other crops | 42 | 42 | 37 | 41 | 40 | 45 | 48 | 76 | 41 | 39 | 43 |
| Fat | Cereals | 5 | 7 | 3 | 3 | 4 | 4 | 4 | 5 | 4 | 4 | 3 |
| | Roots | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| | Sugar crops | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | Pulses | 6 | 5 | 8 | 7 | 8 | 6 | 5 | 5 | 6 | 5 | 4 |
| | Oil crops | 110 | 105 | 113 | 97 | 110 | 93 | 110 | 108 | 112 | 112 | 110 |
| | Vegetables, fruits | 7 | 5 | 6 | 8 | 7 | 7 | 7 | 7 | 6 | 6 | 7 |
| | Meat (ruminants) | 73 | 67 | 74 | 68 | 64 | 60 | 53 | 63 | 60 | 64 | 66 |
| | Pigs, poultry, eggs | 72 | 84 | 81 | 91 | 79 | 89 | 80 | 85 | 87 | 88 | 85 |
| | Milk, butter, dairy | 65 | 59 | 62 | 61 | 68 | 44 | 64 | 57 | 73 | 66 | 66 |
| | Fish | 38 | 36 | 40 | 32 | 35 | 34 | 31 | 51 | 46 | 40 | 35 |
| | Other crops | 70 | 46 | 65 | 46 | 38 | 46 | 67 | 51 | 71 | 70 | 72 |
| Carbohydrates | Cereals | 206 | 207 | 212 | 219 | 214 | 218 | 213 | 212 | 211 | 211 | 211 |
| | Roots | 230 | 237 | 228 | 233 | 231 | 238 | 226 | 232 | 229 | 228 | 227 |
| | Sugar crops | 258 | 258 | 258 | 257 | 257 | 256 | 258 | 258 | 258 | 258 | 258 |
| | Pulses | 176 | 178 | 171 | 173 | 176 | 179 | 177 | 180 | 177 | 178 | 182 |
| | Oil crops | 3 | 8 | 0 | 17 | 4 | 26 | 3 | 6 | 1 | 0 | 4 |
| | Vegetables, fruits | 246 | 255 | 245 | 228 | 241 | 244 | 247 | 252 | 253 | 247 | 251 |
| | Meat (ruminants) | 0 | 1 | 0 | 0 | 0 | 3 | 0 | 3 | 1 | 1 | 1 |
| | Pigs, poultry, eggs | 1 | 0 | 1 | 1 | 6 | 1 | 0 | 2 | 0 | 0 | 0 |
| | Milk, butter, dairy | 55 | 68 | 64 | 60 | 56 | 97 | 54 | 69 | 38 | 54 | 54 |
| | Fish | 1 | 1 | 0 | 21 | 0 | 2 | 7 | 4 | 4 | 3 | 5 |
| | Other crops | 51 | 105 | 66 | 105 | 125 | 101 | 52 | 60 | 50 | 54 | 46 |

**Table A 3. Diet in kilocalories per capita per day and grams protein per capita and day for 11 world regions in 2000**

| | N Africa W Asia | Sub-Sah. Africa | C. Asia, Russ. Fed. | E. Asia | S. Asia | S.-E. Asia | N. America | Lat. Am., Carribean | W. Europe | E.&S.E. Europe | Oceania, Australia | World |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a) Kcal/cap/d | | | | | | | | | | | | |
| Cereals | 1,667 | 1,110 | 1,302 | 1,603 | 1,464 | 1,681 | 996 | 1,089 | 988 | 1,281 | 970 | 1,390 |
| Roots | 70 | 413 | 182 | 161 | 48 | 107 | 108 | 119 | 137 | 194 | 116 | 145 |
| Sugarcrops | 272 | 111 | 329 | 92 | 237 | 204 | 642 | 478 | 373 | 353 | 379 | 245 |
| Pulses | 72 | 88 | 7 | 15 | 94 | 28 | 44 | 104 | 32 | 24 | 18 | 56 |
| Oilcrops | 341 | 248 | 236 | 301 | 251 | 317 | 672 | 306 | 502 | 282 | 456 | 318 |
| Vegetables, fruits | 204 | 112 | 109 | 186 | 95 | 107 | 217 | 166 | 274 | 156 | 194 | 153 |
| Meat (ruminants) | 66 | 47 | 126 | 47 | 21 | 19 | 126 | 125 | 115 | 69 | 218 | 59 |
| Pigs, poultry, eggs | 71 | 35 | 153 | 433 | 20 | 130 | 451 | 234 | 466 | 350 | 275 | 221 |
| Milk, butter, dairy | 145 | 52 | 294 | 31 | 158 | 22 | 417 | 180 | 427 | 316 | 320 | 146 |
| Fish | 15 | 14 | 29 | 56 | 10 | 47 | 31 | 19 | 50 | 21 | 38 | 31 |
| Other crops | 34 | 16 | 18 | 12 | 28 | 15 | 44 | 15 | 64 | 26 | 31 | 24 |
| Total | 2,958 | 2,247 | 2,784 | 2,935 | 2,425 | 2,677 | 3,748 | 2,836 | 3,431 | 3,072 | 3,017 | 2,788 |
| b) g protein/cap/d | | | | | | | | | | | | |
| Cereals | 48 | 28 | 36 | 33 | 34 | 34 | 26 | 26 | 27 | 35 | 27 | 33 |
| Roots | 1 | 4 | 4 | 2 | 1 | 1 | 3 | 2 | 3 | 5 | 3 | 2 |
| Sugarcrops | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pulses | 5 | 6 | 0 | 1 | 6 | 2 | 3 | 7 | 2 | 2 | 1 | 3 |
| Oilcrops | 1 | 3 | 0 | 6 | 1 | 7 | 3 | 2 | 1 | 1 | 2 | 3 |
| Vegetables and fruits | 5 | 2 | 3 | 8 | 3 | 3 | 5 | 3 | 6 | 4 | 4 | 4 |
| Meat (ruminants) | 5 | 4 | 10 | 4 | 2 | 2 | 15 | 12 | 12 | 7 | 21 | 6 |
| Pigs, poultry, eggs | 6 | 2 | 9 | 18 | 1 | 6 | 29 | 12 | 24 | 17 | 15 | 11 |
| Milk, butter, dairy | 7 | 3 | 15 | 2 | 7 | 1 | 22 | 10 | 21 | 16 | 16 | 7 |
| Fish | 2 | 2 | 4 | 8 | 2 | 7 | 5 | 2 | 7 | 3 | 6 | 5 |
| Other crops | 1 | 1 | 1 | 0 | 1 | 1 | 2 | 1 | 3 | 1 | 1 | 1 |
| Total | 83 | 55 | 83 | 83 | 58 | 63 | 114 | 77 | 106 | 89 | 95 | 75 |

**Table A 4. 'Western high meat' diet in 2050, kilocalories per capita per day and grams protein per capita and day for 11 world regions**

| | N Africa W Asia | Sub-Sah. Africa | C. Asia, Russ. Fed. | E. Asia | S. Asia | S.-E. Asia | N. America | Lat. Am., Carribean | W. Europe | E.&S.E. Europe | Oceania, Australia | World |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a) Kcal/cap/d | | | | | | | | | | | | |
| Cereals | 1 338 | 1 054 | 1 268 | 1 309 | 1 395 | 1 417 | 1 140 | 1 204 | 1 122 | 1 123 | 1 155 | 1 264 |
| Roots | 56 | 393 | 177 | 131 | 46 | 90 | 124 | 132 | 155 | 170 | 138 | 153 |
| Sugarcrops | 307 | 176 | 404 | 143 | 277 | 223 | 413 | 423 | 361 | 470 | 384 | 261 |
| 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, fruits | 353 | 302 | 354 | 387 | 267 | 303 | 403 | 378 | 394 | 415 | 418 | 330 |
| Meat (ruminants) | 171 | 192 | 157 | 71 | 58 | 59 | 118 | 168 | 104 | 88 | 250 | 111 |
| Pigs, poultry, eggs | 184 | 145 | 190 | 655 | 55 | 396 | 423 | 317 | 419 | 444 | 314 | 279 |
| Milk, butter, dairy | 378 | 213 | 367 | 47 | 436 | 68 | 391 | 244 | 384 | 401 | 366 | 268 |
| Fish | 9 | 5 | 29 | 52 | 6 | 32 | 22 | 13 | 47 | 21 | 24 | 20 |
| Other crops | 59 | 43 | 59 | 25 | 78 | 42 | 83 | 34 | 92 | 71 | 68 | 55 |
| Total | 3 300 | 3 000 | 3 300 | 3 300 | 3 000 | 3 000 | 3 600 | 3 300 | 3 600 | 3 600 | 3 600 | 3 171 |
| b) g protein/cap/d | | | | | | | | | | | | |
| Cereals | 39 | 27 | 35 | 27 | 33 | 29 | 30 | 28 | 31 | 31 | 33 | 30 |
| Roots | 1 | 4 | 4 | 2 | 1 | 1 | 3 | 2 | 4 | 4 | 3 | 2 |
| Sugarcrops | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pulses | 4 | 5 | 0 | 1 | 5 | 1 | 3 | 7 | 2 | 1 | 1 | 4 |
| Oilcrops | 2 | 5 | 0 | 9 | 1 | 7 | 2 | 1 | 1 | 1 | 2 | 4 |
| Vegetables and fruits | 9 | 6 | 10 | 16 | 8 | 8 | 9 | 7 | 8 | 11 | 8 | 9 |
| Meat (ruminants) | 14 | 18 | 12 | 7 | 6 | 6 | 14 | 17 | 11 | 8 | 23 | 11 |
| Pigs, poultry, eggs | 15 | 8 | 12 | 27 | 3 | 18 | 27 | 17 | 21 | 21 | 17 | 14 |
| Milk, butter, dairy | 19 | 11 | 18 | 3 | 19 | 4 | 21 | 13 | 19 | 20 | 18 | 13 |
| Fish | 1 | 1 | 4 | 8 | 1 | 5 | 4 | 2 | 6 | 3 | 4 | 3 |
| Other crops | 2 | 2 | 2 | 1 | 3 | 2 | 4 | 3 | 4 | 3 | 3 | 2 |
| Total | 106 | 86 | 99 | 100 | 80 | 81 | 118 | 97 | 107 | 103 | 112 | 92 |

**Table A 5. 'Current trend' diet in 2050, kilocalories per capita per day and grams protein per capita and day for 11 world regions**

| | N Africa W Asia | Sub-Sah. Africa | C. Asia, Russ. Fed. | E. Asia | S. Asia | S.-E. Asia | N. America | Lat. Am., Carribean | W. Europe | E.&S.E. Europe | Oceania, Australia | World |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a) Kcal/cap/d | | | | | | | | | | | | |
| Cereals | 1,690 | 1,400 | 1,320 | 1,610 | 1,500 | 1,600 | 996 | 1,100 | 990 | 1,250 | 1,00 | 1,429 |
| Roots | 60 | 420 | 200 | 130 | 50 | 110 | 106 | 120 | 130 | 190 | 110 | 158 |
| Sugarcrops | 330 | 185 | 410 | 140 | 310 | 300 | 650 | 530 | 420 | 410 | 415 | 301 |
| 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 | 373 |
| Vegetables, fruits | 220 | 140 | 115 | 190 | 110 | 110 | 216 | 170 | 270 | 152 | 200 | 155 |
| 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 | 206 |
| 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 |
| Other crops | 34 | 16 | 21 | 10 | 30 | 10 | 44 | 10 | 50 | 15 | 30 | 22 |
| Total | 3,194 | 2,801 | 3,075 | 3,143 | 2,751 | 2,862 | 3,749 | 3,063 | 3,524 | 3,253 | 3,214 | 2,993 |
| b) g protein/cap/d | | | | | | | | | | | | |
| Cereals | 49 | 35 | 36 | 34 | 35 | 32 | 26 | 26 | 27 | 34 | 28 | 34 |
| Roots | 1 | 4 | 5 | 2 | 1 | 1 | 3 | 2 | 3 | 5 | 3 | 2 |
| Sugarcrops | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pulses | 5 | 6 | 1 | 1 | 6 | 2 | 3 | 7 | 2 | 2 | 1 | 4 |
| Oilcrops | 2 | 4 | 0 | 7 | 1 | 8 | 3 | 2 | 1 | 1 | 2 | 3 |
| Vegetables and fruits | 6 | 3 | 3 | 8 | 3 | 3 | 5 | 3 | 6 | 4 | 4 | 4 |
| Meat (ruminants) | 8 | 7 | 14 | 7 | 7 | 6 | 16 | 15 | 13 | 10 | 23 | 9 |
| Pigs, poultry, eggs | 6 | 2 | 12 | 20 | 3 | 8 | 29 | 15 | 25 | 19 | 17 | 10 |
| Milk, butter, dairy | 10 | 4 | 15 | 3 | 9 | 3 | 22 | 11 | 22 | 17 | 18 | 8 |
| Fish | 1 | 1 | 4 | 8 | 1 | 5 | 4 | 2 | 6 | 3 | 4 | 3 |
| Other crops | 1 | 1 | 1 | 0 | 1 | 0 | 2 | 1 | 2 | 1 | 1 | 1 |
| Total | 89 | 68 | 92 | 90 | 68 | 68 | 112 | 83 | 108 | 95 | 101 | 79 |

**Table A 6. 'Less meat' diet in 2050, kilocalories per capita per day and grams protein per capita and day for 11 world regions**

| | N Africa W Asia | Sub-Sah. Africa | C. Asia, Russ. Fed. | E. Asia | S. Asia | S.-E. Asia | N. America | Lat. Am., Carribean | W. Europe | E.&S.E. Europe | Oceania, Australia | World |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a) Kcal/cap/d | | | | | | | | | | | | |
| Cereals | 1 453 | 1 186 | 1 633 | 1 773 | 1 475 | 1 738 | 1 481 | 1 463 | 1 480 | 1 731 | 1 606 | 1 499 |
| Roots | 62 | 450 | 228 | 176 | 49 | 106 | 189 | 247 | 205 | 262 | 192 | 192 |
| Sugarcrops | 462 | 201 | 398 | 204 | 307 | 275 | 607 | 377 | 365 | 285 | 274 | 301 |
| 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 | 381 |
| Vegetables, fruits | 183 | 122 | 137 | 203 | 95 | 106 | 322 | 224 | 410 | 210 | 322 | 165 |
| Meat (ruminants) | 82 | 103 | 73 | 33 | 40 | 31 | 44 | 78 | 42 | 42 | 99 | 57 |
| Pigs, poultry, eggs | 88 | 78 | 89 | 300 | 37 | 208 | 159 | 147 | 170 | 214 | 124 | 133 |
| 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 |
| Other crops | 31 | 17 | 23 | 13 | 28 | 15 | 66 | 20 | 96 | 36 | 52 | 27 |
| Total | 3 194 | 2 801 | 3 075 | 3 143 | 2 751 | 2 862 | 3 749 | 3 063 | 3 524 | 3 253 | 3 214 | 2 993 |
| b) g protein/cap/d | | | | | | | | | | | | |
| Cereals | 42 | 30 | 45 | 37 | 35 | 35 | 39 | 34 | 41 | 47 | 45 | 36 |
| Roots | 1 | 5 | 5 | 3 | 1 | 1 | 5 | 4 | 5 | 6 | 5 | 3 |
| Sugarcrops | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pulses | 4 | 5 | 1 | 1 | 6 | 1 | 5 | 9 | 4 | 2 | 3 | 4 |
| Oilcrops | 2 | 5 | 0 | 7 | 1 | 6 | 3 | 1 | 1 | 0 | 1 | 3 |
| Vegetables and fruits | 5 | 2 | 4 | 9 | 3 | 3 | 7 | 4 | 8 | 5 | 6 | 5 |
| Meat (ruminants) | 7 | 9 | 6 | 3 | 4 | 3 | 5 | 8 | 4 | 4 | 9 | 5 |
| Pigs, poultry, eggs | 7 | 4 | 5 | 12 | 2 | 10 | 10 | 8 | 9 | 10 | 7 | 7 |
| Milk, butter, dairy | 9 | 6 | 9 | 1 | 13 | 2 | 8 | 6 | 8 | 10 | 7 | 7 |
| Fish | 1 | 1 | 4 | 8 | 1 | 5 | 4 | 2 | 6 | 3 | 4 | 3 |
| Other crops | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 2 | 4 | 1 | 2 | 1 |
| Total | 80 | 68 | 80 | 81 | 66 | 66 | 90 | 77 | 90 | 90 | 90 | 74 |

**Table A 7. Fair less meat' diet in 2050, kilocalories per capita per day and grams protein per capita and day for 11 world regions**

| | N Africa W Asia | Sub-Sah. Africa | C. Asia, Russ. Fed. | E. Asia | S. Asia | S.-E. Asia | N. America | Lat. Am., Carribean | W. Europe | E.&S.E. Europe | Oceania, Australia | World |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a) Kcal/cap/d | | | | | | | | | | | | |
| Cereals | 1 599 | 1 522 | 1 750 | 1 880 | 1 916 | 1 936 | 1 535 | 1 698 | 1 447 | 1 648 | 1 529 | 1 748 |
| Roots | 67 | 567 | 244 | 189 | 63 | 74 | 154 | 179 | 195 | 249 | 183 | 210 |
| Sugarcrops | 273 | 48 | 246 | 50 | 122 | 78 | 247 | 170 | 194 | 223 | 228 | 120 |
| Pulses | 69 | 168 | 9 | 76 | 134 | 221 | 62 | 156 | 46 | 31 | 46 | 123 |
| Oilcrops | 343 | 107 | 176 | 164 | 130 | 121 | 258 | 109 | 261 | 178 | 274 | 157 |
| Vegetables, fruits | 196 | 153 | 146 | 218 | 124 | 138 | 307 | 249 | 391 | 200 | 306 | 186 |
| Meat (ruminants) | 49 | 75 | 40 | 15 | 30 | 21 | 22 | 49 | 18 | 21 | 48 | 37 |
| Pigs, poultry, eggs | 53 | 56 | 48 | 135 | 28 | 140 | 78 | 92 | 71 | 106 | 60 | 74 |
| Milk, butter, dairy | 108 | 83 | 93 | 10 | 220 | 24 | 72 | 70 | 65 | 96 | 70 | 102 |
| Fish | 9 | 5 | 29 | 52 | 6 | 32 | 22 | 13 | 47 | 21 | 24 | 20 |
| Other crops | 34 | 16 | 18 | 12 | 28 | 15 | 44 | 15 | 64 | 26 | 32 | 23 |
| Total | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 | 2 800 |
| b) g protein/cap/d | | | | | | | | | | | | |
| Cereals | 46 | 39 | 48 | 39 | 45 | 39 | 40 | 40 | 40 | 45 | 43 | 42 |
| Roots | 1 | 6 | 6 | 3 | 1 | 1 | 4 | 3 | 5 | 6 | 4 | 3 |
| Sugarcrops | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Pulses | 4 | 11 | 1 | 5 | 8 | 14 | 4 | 10 | 3 | 2 | 3 | 8 |
| Oilcrops | 1 | 1 | 0 | 3 | 0 | 2 | 1 | 1 | 1 | 0 | 1 | 1 |
| Vegetables and fruits | 5 | 3 | 4 | 9 | 4 | 4 | 7 | 5 | 8 | 5 | 6 | 5 |
| Meat (ruminants) | 4 | 7 | 3 | 1 | 3 | 2 | 3 | 5 | 2 | 2 | 4 | 4 |
| Pigs, poultry, eggs | 4 | 3 | 3 | 6 | 2 | 6 | 5 | 5 | 4 | 5 | 3 | 4 |
| Milk, butter, dairy | 5 | 4 | 5 | 1 | 9 | 1 | 4 | 4 | 3 | 5 | 3 | 5 |
| Fish | 1 | 1 | 4 | 8 | 1 | 5 | 4 | 2 | 6 | 3 | 4 | 3 |
| Other crops | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 2 | 4 | 1 | 2 | 1 |
| Total | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 | 75 |

**Table A 8. Comparison of yields in organic and industrialised (‘conventional’) cropland agriculture in industrialised countries.**

| Rotation | Input of organic fertilizers per year | Input of N-P-K (kg/ha/yr) | Yield per harvest (percentage of best 7 yields in industrialised agriculture) [t/ha/harvest] | Yield per year, reduced by area needed for fallow and/or production of organic fertilizers (percentage of yields in industrialised agriculture) [t/ha/yr] | Comments |
|---|---|---|---|---|---|
| **1.) Sacramento Valley, California** (Clark et al., 1998) | | | | | |
| Maize: Organic 61% of yields of industrialised agriculture. This includes an estimate of the area needed to produce the fodder for the hens, needed to produce the poultry manure. Therefore, additional to the crop yield, the system boundaries of the organic system would include the production of eggs (about 70 hens per hectare). | | | | | |
| 1st: Vetch/Oats+Vetch (cc) – Tomatoes<br>2nd: Vetch/Oats+Vetch (cc) – Safflower<br>3rd: Vetch/Oats+Vetch (cc) – Maize<br>4th: Oats+Vetch (cc) – Beans | 2.25 – 3 t dm of poultry manure | 0-0-0 | 9.5 (86%) | 7.6 (61%) | Organic production system; the production of the organic fertilizers increases the need of land by about 25% |
| 1st: Cover Crop – Tomatoes<br>2nd: Cover Crop – Safflower<br>3rd: Cover Crop – Maize<br>4th: Vetch – Beans | 0 | 70-n.a.-n.a. | 11.1 (100%) | 11.1 (89%) | Industrialised low input system with reduced inputs of synthetic fertilizers, insecticides (reduced by 75%), fungicides (reduced by 51%) and no use of herbicides. |
| 1st: Tomatoes<br>2nd: Safflower<br>3rd: Maize<br>4th: Wheat – Beans | 0 | 140-n.a.-n.a. | 10 (90%) | 12.5 (100%) | Industrialised high input system; note that this system yields two crops in the 4th year. Therefore, the yield per year for maize was increased by 25%. |
| Tomatoes: Organic 54% of yields of the industrialised system. This includes an estimate of the area needed to produce the fodder for the hens, needed to produce the poultry manure. Therefore, additional to the crop yield, the system boundaries of the organic system would include the production of eggs (about 70 hens per hectare). | | | | | |
| 1st: Vetch/Oats+Vetch (cc) – Tomatoes<br>2nd: Vetch/Oats+Vetch (cc) – Safflower<br>3rd: Vetch/Oats+Vetch (cc) – Maize<br>4th: Oats+Vetch (cc) – Beans | 2.25 – 3 t dm of poultry manure | 0-0-0 | 71 (84%) | 57 (54%) | Organic production system; the production of the organic fertilizers increases the area need by about 25% |
| 1st: Cover Crop – Tomatoes<br>2nd: Cover Crop – Safflower<br>3rd: Cover Crop – Maize<br>4th: Vetch – Beans | 0 | 70-n.a.-n.a. | 80 (94%) | 80 (75%) | Industrialised low input system with reduced inputs of synthetic fertilizers, insecticides (reduced by 75%), fungicides (reduced by 51%) and no use of herbicides. |

| Rotation | Input of organic fertilizers per year | Input of N-P-K (kg/ha/yr) | Yield per harvest (percentage of best 7 yields in industrialised agriculture) [t/ha/harvest] | Yield per year, reduced by area needed for fallow and/or production of organic fertilizers (percentage of yields in industrialised agriculture) [t/ha/yr] | Comments |
|---|---|---|---|---|---|
| 1st: Cover Crop – Tomatoes<br>2nd: Cover Crop – Safflower<br>3rd: Cover Crop – Maize<br>4th: Vetch – Beans | 0 | 140-n.a.-n.a. | 85 (100%) | 106 (100%) | Industrialised high input system; note that this system yields two crops in the 4th year. Therefore, the yield per year for tomatoes was increased by 25%. |
| 1st: Cover Crop – Tomatoes<br>2nd: Wheat | 0 | 140-n.a.-n.a. | 79 (93%) | 79 (75%) | Industrialised high input system, 2year-rotation; note that this system yields two crops in the 4th year, i.e., the yield per year for tomatoes was increased by 25%. |
| **2) Greenfield, Iowa** (Delate and Cambardella, 2004) | | | | | |
| Maize: Organic 51% of the yields of the industrialised system. This includes an estimate of the area needed to produce the fodder for the swines, needed to produce the swine manure. Therefore, additional to the crop yield, the system boundaries of the organic system would include the production of meat (about 1 swine/ha) as well as the meat produced by the alfalfa/oat fed to ruminants. | | | | | |
| 1st: Maize – Winter Rye (cc)<br>2nd: Soybeans<br>3rd: Alfalfa+Oat (as hay crop) | Composted swine manure and maize straw[20] | 0-0-0 | 8.4 (91%) | 5.1 (55%) | Organic production system, 3-year-rotation |
| 1st: Maize – Winter Rye (cc)<br>2nd: Soybeans<br>3rd: Alfalfa+Oat (as hay crop)<br>4th Alfalfa (as hay crop) | Composted swine manure and maize straw[1] | 0-0-0 | 8.5 (92%) | 4.25 (46%) | Organic production system, 4-year-rotation |
| 1st: Maize<br>2nd: Soybeans | 0 | 151-n.a.-n.a. | 9.2 (100%) | 9.2 (100%) | Industrialised production system |
| Soybeans: Organic 58% of the yields in the industrialised system. This includes an estimate of the area needed to produce the fodder for the swines, needed to produce the swine manure. Therefore, additional to the crop yield, the system boundaries of the organic system would include the production of meat (about 0.75 swine/ha) as well as the meat produced by the alfalfa fed to ruminants. | | | | | |

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[20] Intended to apply the same amount of N as in conventional fields.

| Rotation | Input of organic fertilizers per year | Input of N-P-K (kg/ha/yr) | Yield per harvest (percentage of best 7 yields in industrialised agriculture) [t/ha/harvest] | Yield per year, reduced by area needed for fallow and/or production of organic fertilizers (percentage of yields in industrialised agriculture) [t/ha/yr] | Comments |
|---|---|---|---|---|---|
| 1st: Maize – Winter Rye (cc)<br>2nd: Soybeans<br>3rd: Alfalfa+Oat (as hay crop) | Composted swine manure and maize straw[1] | 0-0-0 | 2.9 (97%) | 1.9 (63%) | Organic production system, 3-year-rotation |
| 1st: Maize – Winter Rye (cc)<br>2nd: Soybeans<br>3rd: Alfalfa+Oat (as hay crop)<br>4th Alfalfa (as hay crop) | Composted swine manure and maize straw[1] | 0-0-0 | 3.1 (103%) | 1.6 (53%) | Organic production system, 4-year-rotation |
| 1st: Maize<br>2nd: Soybeans | 0 | 151-n.a.-n.a. | 3.0 (100%) | 3.0 (100%) | Industrialised production system |
| **3) Therwil, Switzerland** (Mäder et al., 2002) | | | | | |
| Winter Wheat: | | | | | |
| 1st: Potatoes<br>2nd: Winter Wheat – Fodder Intercrop<br>3rd: Beetroots<br>4th: Winter Wheat<br>5th: Grass+Clover<br>6th: Grass+Clover | n.a. | 0-0-0 | 4.5 (87%) | 3.0 (86%) | Organic production system (average of bio-organic and bio-dynamic and all given values, derived from graph); values given in dry matter, reconverted into fresh matter by assuming a water content of 14% |
| 1st: Potatoes<br>2nd: Winter Wheat – Fodder Intercrop<br>3rd: Beetroots<br>4th: Winter Wheat<br>5th: Grass+Clover<br>6th: Grass+Clover | n.a. | | 5.2 (100%) | 3.5 (100%) | Industrialised production system (average of two types and all given values, derived from graph); values given in dry matter, reconverted into fresh matter by assuming a water content of 14% |
| Potatoes: | | | | | |
| 1st: Potatoes<br>2nd: Winter Wheat – Fodder Intercrop<br>3rd: Beetroots<br>4th: Winter Wheat | n.a. | 0-0-0 | 33.3 (71%) | 22.2 (71%) | Organic production system (average of bio-organic and bio-dynamic and all given values, derived from graph); values given |

| Rotation | Input of organic fertilizers per year | Input of N-P-K (kg/ha/yr) | Yield per harvest (percentage of best 7 yields in industrialised agriculture) [t/ha/harvest] | Yield per year, reduced by area needed for fallow and/or production of organic fertilizers (percentage of yields in industrialised agriculture) [t/ha/yr] | Comments |
|---|---|---|---|---|---|
| 5th: Grass+Clover<br>6th: Grass+Clover | | | | | in dry matter, reconverted into fresh matter by assuming a water content of 14% |
| 1st: Potatoes<br>2nd: Winter Wheat – Fodder Intercrop<br>3rd: Beetroots<br>4th: Winter Wheat<br>5th: Grass+Clover<br>6th: Grass+Clover | n.a. | | 47.0 (100%) | 31.3 (100%) | Industrialised production system (average of two types and all given values, derived from graph); values given in dry matter, reconverted into fresh matter by assuming a water content of 14% |

**Table A 9. Comparison of yields in industrialised and organic farming in developing countries.**

| Rotation | Input of organic fertilizers | Input of N-P-K [kg/ha/yr] | Yield per harvest event [t/ha/harvest] | Comments |
|---|---|---|---|---|
| **1.) Bolivia** (Rist, 1992cited in Altieri, 1999) | | | | |
| Potatoes | | | | |
| n.a. | n.a. | 0 | 9.2 | Cultivation according to traditional methods |
| n.a. | n.a. | 0 | 11.4 | Yield improvement by organic methods (not further specified) |
| n.a. | n.a. | 80-120-n.a. | 17.6 | Yield improvement by industrial methods |
| **2) Ndiamsil, department of Bambey, Senegal** (Diop, 1999) | | | | |
| Groundnuts | | | | |
| n.a. | 0 | 0-0-0 | 0.34 | Control experiment, no inputs |

| **Rotation** | **Input of organic fertilizers** | **Input of N-P-K [kg/ha/yr]** | **Yield per harvest event [t/ha/harvest]** | **Comments** |
|---|---|---|---|---|
| n.a. | 2 t/ha manure, every 2 years | 0-0-0 | 0.49 | +/- local farmer's practice |
| n.a. | 4 t/ha manure, every 2 years | 0-15-0 | 0.68 | P-Fertilizer containing 37% P, 30 kg/ha every 2 years |
| **2) Ndiamsil, department of Bambey, Senegal** (Diop, 1999, adapted from Westley, 1997) | | | | |
| ***Groundnuts*** | | | | |
| n.a. | 0 | 0-0-0 | 0.34 | Control experiment, no inputs |
| n.a. | 2 t/ha manure | 0-0-0 | 0.62 | |
| n.a. | 4 t/ha manure | 0-0-0 | 0.63 | |
| n.a. | 2 t/ha manure | 0-0-0 | 1.05 | |
| n.a. | 4 t/ha manure | 0-0-0 | 0.97 | |
| ***Millet*** | | | | |
| n.a. | 0 | 0-0-0 | 0.34 | Control experiment, no inputs |
| n.a. | 2 t/ha manure | 0-0-0 | 0.58 | |
| n.a. | 4 t/ha manure | 0-0-0 | 0.63 | |
| n.a. | 2 t/ha compost | 0-0-0 | 1.01 | |
| n.a. | 4 t/ha compost | 0-0-0 | 1.03 | |
| **4.) Tigray, Ethiopia** (Edwards et al., 2007)<br>Development project in 57 local communities. Most locations in areas with poor (degraded) soils and erratic rainfalls. P fertilizer applied in the form of DAP; straw main source of animal feed during dry season and along with manure important raw materials for making compost; data recorded from 2000 to 2006; in 1998, when the first set of data were collected, the grain yields were considerably lower in the plots without any inputs (395-920 kg/ha for barley, 465-750 kg/ha for durum wheat, 760 kg/ha for finger millet, 590-630 kg/ha for hanfets, 480-790 kg/ha for teff), the higher yields in the control plots being a residual effect of the use of compost in previous years. | | | | |
| Barley | | | | |
| n.a. | 0 | 0-0-0 | 1.12 | 2.48 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 2.34 | 4.46 |
| n.a. | 0 | 120-120-0 | 1.86 | 3.74 |
| Durum wheat | | | | |
| n.a. | 0 | 0-0-0 | 1.23 | 2.34 |

| **Rotation** | **Input of organic fertilizers** | **Input of N-P-K [kg/ha/yr]** | **Yield per harvest event [t/ha/harvest]** | **Comments** |
|---|---|---|---|---|
| n.a. | 5-15 t/ha compost | 0-0-0 | 2.49 | 3.82 |
| n.a. | 0 | 120-120-0 | 1.69 | 3.41 |
| Finger millet | | | | |
| n.a. | 0 | 0-0-0 | 1.14 | 2.24 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 2.65 | 4.75 |
| n.a. | 0 | 120-120-0 | 1.85 | 3.84 |
| Hanfets[21] | | | | |
| n.a. | 0 | 0-0-0 | 0.86 | 2.24 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 1.34 | 3.40 |
| n.a. | 0 | 120-120-0 | 1.20 | 2.24 |
| Maize | | | | |
| n.a. | 0 | 0-0-0 | 1.76 | 3.53 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 3.75 | 4.96 |
| n.a. | 0 | 120-120-0 | 2.90 | 3.86 |
| Sorghum | | | | |
| n.a. | 0 | 0-0-0 | 1.34 | 2.45 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 2.50 | 3.66 |
| n.a. | 0 | 120-120-0 | 2.48 | 4.43 |
| Teff | | | | |
| n.a. | 0 | 0-0-0 | 1.15 | 2.47 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 2.14 | 3.80 |
| n.a. | 0 | 120-120-0 | 1.68 | 3.52 |
| | | | | |

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[21] Mixture of barley and durum wheat

| **Rotation** | **Input of organic fertilizers** | **Input of N-P-K [kg/ha/yr]** | **Yield per harvest event [t/ha/harvest]** | **Comments** |
|---|---|---|---|---|
| Faba bean | | | | |
| n.a. | 0 | 0-0-0 | 1.38 | 2.12 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 2.86 | 4.16 |
| n.a. | 0 | 120-120-0 | 2.70 | 3.78 |
| Field pea | | | | |
| n.a. | 0 | 0-0-0 | 1.53 | 1.20 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 1.96 | 1.63 |
| n.a. | 0 | 120-120-0 | 0 | 0 |
| Average all crops | | | | |
| n.a. | 0 | 0-0-0 | 1.20 | 2.45 |
| n.a. | 5-15 t/ha compost | 0-0-0 | 2.47 | 4.07 |
| n.a. | 0 | 120-120-0 | 1.81 | 3.40 |
| **5.) China/India; yields given as average of several years** (Giovannucci 2005) | | | | |
| Rice (China, Jiangxi, highland) | | | | |
| n.a. | n.a. | n.a. | 3.63 | Traditional production method |
| n.a. | n.a. | 0-0-0 | 5.88 | Organic production method |
| n.a. | n.a. | n.a. | 6.73 | Industrialised production method |
| Ginger (China, Jiangxi, highland) | | | | |
| n.a. | n.a. | n.a. | n.a. | Traditional production method |
| n.a. | n.a. | 0-0-0 | 16.50 | Organic production method |
| n.a. | n.a. | n.a. | 20.55 | Industrialised production method |
| Soy (China, Jiangxi, highland) | | | | |
| n.a. | n.a. | n.a. | n.a. | Traditional production method |
| n.a. | n.a. | 0-0-0 | 3.75 | Organic production method |
| n.a. | n.a. | n.a. | 7.50 | Industrialised production method |

| **Rotation** | **Input of organic fertilizers** | **Input of N-P-K [kg/ha/yr]** | **Yield per harvest event [t/ha/harvest]** | **Comments** |
|---|---|---|---|---|
| **Rice (India, Karnataka, dry valley)** | | | | |
| n.a. | n.a. | n.a. | 3.15 | Traditional production method |
| n.a. | n.a. | 0-0-0 | 4.85 | Organic production method |
| n.a. | n.a. | n.a. | 5.13 | Industrialised production method |
| Sugar cane (India, Karnataka, dry valley) | | | | |
| n.a. | n.a. | n.a. | 96.63 | Traditional production method |
| n.a. | n.a. | 0-0-0 | 119.38 | Organic production method |
| n.a. | n.a. | n.a. | 124.25 | Industrialised production method |
| Banana (India, Karnataka, dry valley) | | | | |
| n.a. | n.a. | n.a. | 19.25 | Traditional production method |
| n.a. | n.a. | 0-0-0 | 29.88 | Organic production method |
| n.a. | n.a. | n.a. | 27.75 | Industrialised production method |
| **6.) Central India, comparison of 60 organic and 60 industrialised farms during two years** (Kilcher 2007) | | | | |
| n.a. | n.a. | 0-0-0 | 1.35 | Organic production method |
| n.a. | n.a. | 0-0-0 | 1.29 | Industrialised production method |
| **7.) Kenya, bimodal rainfall, fallow-crop rotation every year** (Niang et al., 1998, Rao et al., 1998, cited in Sanchez et al., 2000) | | | | |
| fallow-maize | n.a. | n.a. | Tripling of maize yields | Yearly rotation between fallow in first raining and maize in second raining season. |

**Table A 10. Characteristics of intensive, organic and humane cattle systems**

| Livestock type / reference | Keeping type | Body weight [kg] | Hot Carcass Weight [kg] | Beef production [kg/ha] | Stocking rate $^{a}$[animals /ha] $^{b}$[livestock units/ha] | Liveweight gain [kg/ha] | Milk yield $^{a}$[l/cow] $^{b}$[l/ha/yr] $^{c}$[kg milk / cow] | Combined yield [l/ha] | Comment |
|---|---|---|---|---|---|---|---|---|---|
| Neel et al., 2007 | | | | | | | | | |
| Cattle | Pasture finishing system | 475 (87.8%) | 247 (76%) | | | | | | |
| | Corn-silage concentrate | 541 | 325 | | | | | | |
| Extensive Agriculture Branch - DPIW, 2009 | | | | | | | | | |
| Cattle | Nil N | | | 962 (57.5%, 48.6%) | | | | | |
| | 30 kg/ha N each rotation | | | 1672 | | | | | |
| | 30 kg/ha N each rotation + Irrigation | | | 1981 | | | | | |
| Younie, 2001 | | | | | | | | | |
| Cattle | Organic | | 267 (99.6%) | | 3.42$^{a}$ (76.7%) | 1481 (77.1%) | | | |
| | Intensive | | 268 | | 4.46$^{a}$ | 1921 | | | 270 kg N/ha/yr |
| Haas et al., 2001 | | | | | | | | | |
| Cattle | Organic | | | | 1.9$^{b}$ (86.4%) | | 5275$^{a}$ (78.1%) | | |
| | Extensive | | | | 1.9$^{b}$ (86.4%) | | 6390$^{a}$ (94.6%) | | |
| | Intensive | | | | 2.2$^{b}$ | | 6758$^{a}$ | | |
| Padel, 2000 | | | | | | | | | |
| Cattle | Organic | | | | 1.5$^{b}$ (83.3%) | | 5269$^{a}$ (90.0%) | 7904 (75.0%) | |
| | Intensive | | | | 1.8$^{b}$ | | 5854$^{a}$ | 10537 | |
| Rosati and Aumayr, 2004 | | | | | | | | | |
| Cattle | Organic | | | | | | 5130$^{b}$ (70.7%) | | |
| | Intensive | | | | | | 7260$^{b}$ | | |
| Kristensen and Kristensen, 1998 | | | | | | | | | |
| Cattle | Organic | 573 (99.3%) | | | | | 7164$^{c}$ (98.4%) | | |
| | Intensive | 577 | | | | | 7279$^{c}$ | | |

**Table A 11. Characteristics of intensive, organic and humane poultry systems.**

| **Livestock type** | **Keeping type** | **Carcass weight [kg]** | **Feed intake [g]** | **Feed efficiency [g feed : g gain]** | **Comment** |
|---|---|---|---|---|---|
| Castellini et al., 2002 | | | | | |
| Poultry | Organic | After 56d: 2.01 (88.9%)<br>After 81d: 2.54 (82.7%) | | | 4 m²/bird grass paddock |
| | Intensive | After 56d: 2.26<br>After 81d: 3.07 | | | 0.12 m² / bird |
| Fanatico et al., 2008 | | | | | |
| Poultry | Outdoor access | 1.65 (105.1%) | 8.46 (125.3%) | 3.75 (116.8%) | Slow growing genotypes |
| | Only indoor | 1.57 | 6.75 | 3.21 | Slow growing genotypes |

**Table A 12. Characteristics of intensive, organic and human pig rearing systems.**

| Livestock type | Keeping type | Live Weight [kg] | Hot Carcass weight [kg] | Feed intake $^{a}$[kg/d] $^{b}$[kg/pig] | Feed efficiency [kg feed : kg gain] | Growth rate [g/d] | Comment |
|---|---|---|---|---|---|---|---|
| Sundrum et al., 2000 | | | | | | | |
| Pig | Organic | | | | 2.58 (95.2%) | | faba beans + potato protein |
| | Organic | | | | 2.78 (102.6%) | | peas + lupines |
| | Organic | | | | 2.81 (103.6%) | | faba beans + lupines |
| | Intensive | | | | | | |
| Lebret et al., 2006 | | | | | | | |
| Pig | Outdoor | 116.6 (106.4%) | | 2.94 $^{a}$ (108.5%) | | 1045 (108.8%) | + 2.4 m²/pig |
| | Indoor | 109.6 | | 2.71 $^{a}$ | | 960 | 0.65 m² / pig |
| British Pig Executive, 2009 | | | | | | | |
| Pig | Outdoor | | | 72.88$^{b}$ (114.6%) | | | |
| | Indoor | | | 63.59$^{b}$ | | | |
| {Gentry, 2002 27017 /id | | | | | | | |
| Pig | Outdoor | | 87.2 (104.4%) | | | | Alfala pasture at 212 m² / pig |
| | Indoor | | 83.5 | | | | Concrete slatted floors at 1.2 m² / pig |
| Bornett et al., 2003 | | | | | | | |
| Pig | Organic | | | | 2.64 (126.8%) | | |
| | Free-range | | | | 2.41 (124.2%) | | |
| | Freedom Food | | | | 2.05 (105.7%) | | |
| | Partly-slatted | | | | 1.92 (98.9%) | | |
| | Fully-slatted | | | | 1.94 | | |

**Table A 13. Main global results of the 44 feasible scenarios**

| Diet | Livestock | yields | Land use | Vegetable Food [1000 tdm/yr] | Animal Products [1000 tdm/yr] | Others (Fibres etc.) [1000 tdm/yr] | Total [1000 tdm/yr] | Feed input of monogastric species [1000 tdm/yr] | Feed input of ruminants - cropland [1000 tdm/yr] | Feed input of ruminants - grazing land [1000 tdm/yr] | Total Feed input [1000 tdm/yr] | Bio-energy crops on cropland [1000 tdm/yr] | Residues from cropland (gross, excl. bedding) [1000 tdm/yr] | Bio-energy potential on grazing land [1000 tdm/yr] | Bio-energy total [1000 tdm/yr] | Bio-energy total [EJ/yr] | Harvest on Cropland [1000 tdm/yr] | Harvest on Grazing land [1000 tdm/yr] | Total [1000 tdm/yr] | Grazing intensity [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Western | intensive | FAO | mass. | 1.958 | 367 | 143 | 2.468 | 1.408 | 2.947 | 4.671 | 9.025 | -562 | 1.639 | 2.053 | 3.130 | 58 | 6.387 | 4.671 | 11.058 | 26% |
| Current | intensive | FAO | mass. | 1.964 | 264 | 121 | 2.349 | 1.025 | 2.505 | 3.804 | 7.335 | 1.622 | 1.709 | 2.641 | 5.972 | 110 | 7.081 | 3.804 | 10.886 | 21% |
| Current | intensive | FAO | BAU | | | | | 1.025 | 2.528 | 4.067 | 7.620 | 971 | 1.494 | 3.194 | 5.660 | 105 | 6.367 | 4.067 | 10.434 | 21% |
| Current | intensive | interm. | mass. | | | | | 1.025 | 2.172 | 3.947 | 7.144 | 1.053 | 1.439 | 2.546 | 5.038 | 93 | 6.206 | 3.947 | 10.153 | 22% |
| Current | intensive | interm. | BAU | | | | | 1.025 | 2.209 | 4.221 | 7.455 | 352 | 1.237 | 3.085 | 4.674 | 86 | 5.457 | 4.221 | 9.679 | 22% |
| Current | humane | FAO | mass. | | | | | 1.094 | 2.568 | 3.944 | 7.606 | 1.516 | 1.698 | 2.547 | 5.761 | 107 | 7.113 | 3.944 | 11.056 | 22% |
| Current | humane | FAO | BAU | | | | | 1.094 | 2.590 | 4.199 | 7.883 | 773 | 1.483 | 3.097 | 5.354 | 99 | 6.305 | 4.199 | 10.504 | 22% |
| Current | humane | interm. | mass. | | | | | 1.094 | 2.239 | 4.102 | 7.435 | 781 | 1.428 | 2.441 | 4.649 | 86 | 6.075 | 4.102 | 10.177 | 22% |
| Current | humane | interm. | BAU | | | | | 1.094 | 2.273 | 4.378 | 7.745 | 73 | 1.225 | 2.968 | 4.267 | 79 | 5.318 | 4.378 | 9.696 | 23% |
| Current | organic | FAO | mass. | | | | | 1.179 | 2.652 | 4.062 | 7.893 | 1.214 | 1.686 | 2.467 | 5.367 | 99 | 6.988 | 4.062 | 11.050 | 22% |
| Current | organic | FAO | BAU | | | | | 1.179 | 2.672 | 4.312 | 8.163 | 475 | 1.472 | 3.014 | 4.960 | 92 | 6.181 | 4.312 | 10.493 | 22% |
| Current | organic | interm. | mass. | | | | | 1.179 | 2.324 | 4.232 | 7.734 | 397 | 1.416 | 2.353 | 4.166 | 77 | 5.869 | 4.232 | 10.101 | 23% |
| Current | organic | interm. | BAU | | | | | 1.179 | 2.357 | 4.509 | 8.044 | -296 | 1.213 | 2.871 | 3.788 | 70 | 5.420 | 4.509 | 9.929 | 23% |
| less meat | intensive | FAO | mass. | 2.065 | 198 | 124 | 2.387 | 678 | 2.287 | 3.384 | 6.350 | 2.308 | 1.749 | 2.924 | 6.981 | 129 | 7.323 | 3.384 | 10.707 | 19% |
| less meat | intensive | FAO | BAU | | | | | 678 | 2.310 | 3.646 | 6.634 | 1.634 | 1.534 | 3.504 | 6.672 | 123 | 6.585 | 3.646 | 10.231 | 19% |
| less meat | intensive | interm. | mass. | | | | | 678 | 1.954 | 3.517 | 6.149 | 1.921 | 1.480 | 2.834 | 6.236 | 115 | 6.631 | 3.517 | 10.147 | 19% |
| less meat | intensive | interm. | BAU | | | | | 678 | 1.991 | 3.780 | 6.449 | 1.207 | 1.278 | 3.408 | 5.893 | 109 | 5.868 | 3.780 | 9.648 | 20% |
| less meat | intensive | org | mass. | | | | | 678 | 2.011 | 3.507 | 6.196 | -417 | 1.142 | 2.843 | 3.569 | 66 | 4.774 | 3.507 | 8.281 | 19% |
| less meat | humane | FAO | mass. | | | | | 721 | 2.329 | 3.481 | 6.532 | 2.287 | 1.742 | 2.858 | 6.887 | 127 | 7.391 | 3.481 | 10.872 | 19% |
| less meat | humane | FAO | BAU | | | | | 721 | 2.351 | 3.736 | 6.808 | 1.542 | 1.527 | 3.438 | 6.507 | 120 | 6.581 | 3.736 | 10.317 | 19% |
| less meat | humane | interm. | mass. | | | | | 721 | 2.000 | 3.624 | 6.345 | 1.770 | 1.473 | 2.762 | 6.006 | 111 | 6.572 | 3.624 | 10.196 | 20% |
| less meat | humane | interm. | BAU | | | | | 721 | 2.034 | 3.881 | 6.637 | 1.051 | 1.270 | 3.334 | 5.656 | 105 | 5.803 | 3.881 | 9.684 | 20% |
| less meat | humane | org | mass. | | | | | 721 | 2.056 | 3.611 | 6.389 | -650 | 1.135 | 2.773 | 3.258 | 60 | 4.867 | 3.611 | 8.478 | 20% |
| less meat | organic | FAO | mass. | | | | | 775 | 2.392 | 3.558 | 6.724 | 2.083 | 1.734 | 2.807 | 6.624 | 123 | 7.309 | 3.558 | 10.866 | 19% |
| less meat | organic | FAO | BAU | | | | | 775 | 2.412 | 3.807 | 6.993 | 1.343 | 1.519 | 3.386 | 6.249 | 116 | 6.502 | 3.807 | 10.309 | 20% |
| less meat | organic | interm. | mass. | | | | | 775 | 2.063 | 3.708 | 6.545 | 1.511 | 1.464 | 2.707 | 5.682 | 105 | 6.435 | 3.708 | 10.142 | 20% |
| less meat | organic | interm. | BAU | | | | | 775 | 2.096 | 3.959 | 6.829 | 800 | 1.262 | 3.278 | 5.340 | 99 | 5.672 | 3.959 | 9.631 | 20% |

| Diet | Livestock | yields | Land use | Vegetable Food [1000 tdm/yr] | Animal Products [1000 tdm/yr] | Others (Fibres etc.) [1000 tdm/yr] | Total [1000 tdm/yr] | Feed input of mono-gastric species [1000 tdm/yr] | Feed input of ru-minants - cropland [1000 tdm/yr] | Feed input of ru-minants - grazing land [1000 tdm/yr] | Total Feed input [1000 tdm/yr] | Bio-energy crops on cropland [1000 tdm/yr] | Residues from cropland (gross, excl. bedding) [1000 tdm/yr] | Bio-energy potential on grazing land [1000 tdm/yr] | Bio-energy total [1000 tdm/yr] | Bio-energy total [EJ/yr] | Harvest on Crop-land [1000 tdm/yr] | Harvest on Grazing land [1000 tdm/yr] | Total [1000 tdm/yr] | Grazing intensity [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| fair | intensive | FAO | mass. | 2.093 | 130 | 122 | 2.345 | 385 | 1.787 | 2.066 | 4.238 | 2.855 | 1.955 | 3.885 | 8.695 | 161 | 7.292 | 2.066 | 9.357 | 11% |
| fair | intensive | FAO | BAU | | | | | 385 | 1.733 | 2.064 | 4.182 | 2.153 | 1.793 | 4.748 | 8.694 | 161 | 6.526 | 2.064 | 8.590 | 11% |
| fair | intensive | interm. | mass. | | | | | 385 | 1.591 | 2.667 | 4.643 | 3.017 | 1.593 | 3.438 | 8.048 | 149 | 7.148 | 2.667 | 9.815 | 15% |
| fair | intensive | interm. | BAU | | | | | 385 | 1.546 | 2.644 | 4.575 | 2.258 | 1.447 | 4.288 | 7.993 | 148 | 6.342 | 2.644 | 8.986 | 14% |
| fair | intensive | org | mass. | | | | | 385 | 1.630 | 2.586 | 4.600 | 304 | 1.268 | 3.498 | 5.071 | 94 | 4.501 | 2.586 | 7.086 | 14% |
| fair | intensive | org | BAU | | | | | 385 | 1.566 | 2.581 | 4.532 | -449 | 1.152 | 4.338 | 5.041 | 93 | 4.147 | 2.581 | 6.728 | 13% |
| fair | humane | FAO | mass. | | | | | 408 | 1.867 | 2.343 | 4.618 | 2.919 | 1.908 | 3.677 | 8.505 | 157 | 7.398 | 2.343 | 9.741 | 13% |
| fair | humane | FAO | BAU | | | | | 408 | 1.811 | 2.340 | 4.559 | 2.141 | 1.746 | 4.527 | 8.414 | 156 | 6.554 | 2.340 | 8.895 | 12% |
| fair | humane | interm. | mass. | | | | | 408 | 1.672 | 2.935 | 5.015 | 2.967 | 1.547 | 3.238 | 7.752 | 143 | 7.144 | 2.935 | 10.079 | 16% |
| fair | humane | interm. | BAU | | | | | 408 | 1.625 | 2.912 | 4.945 | 2.210 | 1.401 | 4.074 | 7.685 | 142 | 6.336 | 2.912 | 9.248 | 15% |
| fair | humane | org | mass. | | | | | 408 | 1.704 | 2.829 | 4.942 | 235 | 1.226 | 3.317 | 4.777 | 88 | 4.475 | 2.829 | 7.305 | 15% |
| fair | humane | org | BAU | | | | | 408 | 1.639 | 2.825 | 4.872 | -521 | 1.111 | 4.143 | 4.732 | 88 | 4.189 | 2.825 | 7.014 | 15% |
| fair | organic | FAO | mass. | | | | | 437 | 1.939 | 2.498 | 4.874 | 2.803 | 1.880 | 3.561 | 8.245 | 153 | 7.350 | 2.498 | 9.849 | 14% |
| fair | organic | FAO | BAU | | | | | 437 | 1.881 | 2.498 | 4.817 | 2.029 | 1.718 | 4.401 | 8.148 | 151 | 6.509 | 2.498 | 9.008 | 13% |
| fair | organic | interm. | mass. | | | | | 437 | 1.740 | 3.068 | 5.245 | 2.814 | 1.522 | 3.139 | 7.476 | 138 | 7.060 | 3.068 | 10.128 | 17% |
| fair | organic | interm. | BAU | | | | | 437 | 1.692 | 3.048 | 5.177 | 2.064 | 1.376 | 3.966 | 7.406 | 137 | 6.258 | 3.048 | 9.306 | 16% |
| fair | organic | org | mass. | | | | | 437 | 1.773 | 2.968 | 5.178 | 45 | 1.201 | 3.214 | 4.460 | 83 | 4.355 | 2.968 | 7.323 | 16% |

Western: Western high meat diet, Current: current trend diet; Less: less meat diet; intensive: intensive livestock systems; interm: intermediate yields; mass: .massive land use change. Note that bioenergy potentials refer to total aboveground production and serve as proxies only. Scenarios in which cropland requirement exceed cropland availability by less than 5% are classified as feasible, despite their negative bioenergy potential on cropland. It was assumed that this biomass has to be produced on grazing land and is thus subtraced from the grazing land bioenergy potential. For details see text.