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How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030?

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ABSTRACT

Growing global population figures and per-capita incomes imply an increase in food demand and pressure to expand agricultural land. Agricultural expansion into natural ecosystems affects biodiversity and leads to substantial carbon dioxide emissions.

Considerable attention has been paid to prospects for increasing food availability, and limiting agricultural expansion, through higher yields on cropland. In contrast, prospects for efficiency improvements in the entire food-chain and dietary changes toward less land-demanding food have not been explored as extensively. In this study, we present model-based scenarios of global agricultural land use in 2030, as a basis for investigating the potential for land-minimized growth of world food supply through: (i) faster growth in feed-to-food efficiency in animal food production; (ii) decreased food wastage; and (iii) dietary changes in favor of vegetable food and less land-demanding meat. The scenarios are based in part on projections of global food agriculture for 2030 by the Food and Agriculture Organization of the United Nations, FAO. The scenario calculations were carried out by means of a physical model of the global food and agriculture system that calculates the land area and crops/pasture production necessary to provide for a given level of food consumption.

In the reference scenario – developed to represent the FAO projections – global agricultural area expands from the current 5.1 billion ha to 5.4 billion ha in 2030. In the faster-yet-feasible livestock productivity growth scenario, global agricultural land use decreases to 4.8 billion ha. In a third scenario, combining the higher productivity growth with a substitution of pork and/or poultry for 20% of ruminant meat, land use drops further, to 4.4 billion ha. In a fourth scenario, applied mainly to high-income regions, that assumes a minor transition towards vegetarian food (25% decrease in meat consumption) and a somewhat lower food wastage rate, land use in these regions decreases further, by about 15%.

1. Introduction

According to the Millennium Ecosystem Assessment (MEA, 2005), the most important direct driver of terrestrial ecosystem change during the past 50 years has been land cover change, in particular the conversion of ecosystems to agricultural land. Together with the adoption of new technologies and increased agricultural inputs, the expansion of agricultural land has enabled an extraordinary progress in nutrition levels and food security. Despite this, however, undernourishment still affects about 920 million people in low and medium-income regions (FAO, 2008).

Still-growing global population figures and per-capita incomes and the need to decrease undernourishment imply increased pressure on the global food supply system. This amplifies the risk of further expansion of agricultural land into forests and other land with high biodiversity values. In addition, if stringent policies aimed at curbing climatic change are implemented – by substantially increasing the cost of emitting carbon dioxide (CO_2) through taxes or emissions cap and trade schemes – demand for biomass for energy purposes is likely to increase dramatically (Gielen et al., 2003; van Vuuren et al., 2004).

Clearly, curbing food and bioenergy-driven agricultural expansion is critical to conserving natural ecosystems and global biodiversity. Limiting expansion, particularly conversion of forests into cropland and pastures, is also essential for mitigating global CO_2 emissions (Gitz and Ciais, 2004; Fargione et al., 2008; Burneya et al., 2010). Limiting the land area used for livestock production – which currently accounts for about 80% of total agricultural land use – is consequently considered a key approach in reducing livestock's environmental impact (Steinfeld et al., 2006).

There is considerable agreement that increasing yields on existing agricultural land, especially cropland, is a key component for minimizing further expansion (Waggoner, 1994; Goklany, 1998; Ausubel, 2000; Tilman et al., 2002; Cassman et al., 2003; Evans,

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2003; Balmford et al., 2005; Green et al., 2005; Lee et al., 2006; The Royal Society, 2009). There are, however, limitations and negative aspects of further intensification of the use of cropland. The potential for further sustained growth in crop yields is gradually diminishing in several main producer countries, mainly because the exploitable gap between average farm yields and the genetic yield potential is closing. Raising the genetic yield potential of major crops further appears difficult, and even maintaining current yield potentials may prove to be a challenge, as there are signs of intensification-induced declines of the yield potentials over time, related to subtle and complex forms of soil degradation (Cassman, 1999; Pingali and Heisey, 1999). Also, high crop yields depend on large inputs of nutrients, fresh water, and pesticides, and contribute to negative ecosystem effects, such as eutrophication (Tilman et al., 2002).

Besides intensification of cropland use, there are other major – but hitherto less investigated – options, including: (i) increasing the efficiency of the entire food-chain from "field to fork", (ii) changing diets toward food commodities requiring less land, and iii) incrasing the yields and nutritive quality of permanent pastures, which globally amount to 3.5 billion ha – more than twice the area of the global croplands.

Very few studies have been undertaken that consistently address several of these topics. Studies addressing food wastage at the household and retail level are few, examples include Bender (1994), Kantor et al. (1997), Engström and Carlsson-Kanyama (2004) and WRAP (2008). Recent global studies of long-term development of animal food production and feed use include CAST (1999), Delgado et al. (1999), Bouwman et al. (2005), Keyzer et al. (2005), Steinfeld et al. (2006). Numerous studies have stressed the environmentally beneficial effects of changes in food consumption patterns, primarily in substituting vegetable for animal food – recent examples include Gerbens-Leenes and Nonhebel (2002), Smil (2002), Carlsson-Kanyama et al. (2003), de Boer et al. (2006), Elferink and Nonhebel (2007) and Stehfest et al. (2009).

The scenarios in the current study were developed to complement the projections to 2030 in the FAO's "World Agriculture: towards 2015/2030" (Bruinsma, 2003). The FAO study included comprehensive analyses of the prospects for increasing yields and production of cereals and other edible-type crops (sugar crops, oil crops, etc.). However, the FAO study did not include any projections of yield increases and production of permanent pasture and animal forage crops (grasses, etc.), nor of the total use and supply of livestock feed – only feed use of cereals and other edible-type crops was included.

The purpose of this study is to:

I. Complement the FAO projections for the year 2030 by estimating total feed and land requirements implicit in the projections, including estimates of feed supply from by-products/residues, forage crops, and permanent pastures, as well as area and yield of permanent pastures.
II. Estimate the potential until the year 2030 for minimizing agricultural expansion through means other than further intensification in cultivation:
   (a) accelerated growth in feed-to-food efficiency in animal food production
   (b) dietary changes toward less land-demanding animal and vegetable food
   (c) decreased wastage of food at retail and household levels.

In the following section, the model used for creating the scenarios is briefly described. In Section 3, we describe the foundations of the scenarios and the data and methodology used in creating them. Principal results from the scenarios are presented and considered in Section 4, and in Sections 5–6 we discuss the accuracy and relevance of the results, and what conclusions may be drawn from them.

2. Model description

The methodological basis for constructing the scenarios was a physical model of the global food and agriculture system, the ALBIO (Agricultural Land use and BIOmass) model. From a prescribed food consumption level, the ALBIO model calculates the land area and crops/pasture production necessary to provide for that level of food consumption. Major exogenous variables are food consumption, productivity in livestock and crop production, efficiency in food industry, trade, and use of by-products and residues for purposes of animal feeding, bedding, etc. Major endogenous variables are land use and crops and pasture production, as well as production of by-products and residues (e.g. straw, oil cakes, etc.) generated within the food and agriculture system. For each geographical region described, the model contains about 1700 parameters and about 170 physical flows.

There are in total eight regions in the model: West Europe, East Europe (including Russia), North America and Oceania, South and Central Asia, East Asia, Sub-Saharan Africa, Latin America and the Caribbean, and North Africa and West Asia. Trade of food and feedstuffs between these regions is represented in the model. Global trade flows are balanced, i.e. a net import to one region is met by an equally large net export from the other regions combined.

The representation of the plant biomass production comprises all major categories of terrestrial biomass used in the food system. In total about 30 crops and pasture systems are included, with separate descriptions of rainfed and irrigated production. Exogenous parameters in crop systems include yield and cropping intensity, and in pasture systems, yield and pasture utilization.

Production of animal food is represented by nine animal systems (cattle and buffalo milk and meat, sheep meat, goat meat, pork, eggs, and chicken meat). Feed energy requirements are calculated endogenously using standardized bio-energetic equations with basic biological parameters, such as live weight, live-weight gain, reproduction rate, mortality rate and milk/egg production rate, as exogenous parameters. The estimated feed energy requirements are fully met by feed matter intake. The model calculates the feed dry matter intake with feed ration specification (the share of each feedstuff in the ration) and energy content of each feedstuff used as exogenous parameters. The number of individual feedstuffs included in the specification varies from about 20 (chickens) to roughly 45 (pigs and ruminants).

Production of processed vegetable food is represented by 12 separate systems, including major cereal products (flours, rice, etc.), sugars, vegetable oils, and alcoholic beverages. Food use is represented by about 40 separate food commodities, and includes all principal food commodities consumed in each of the world regions.

For further details on the ALBIO model, see Wirsenius (2003a,b, 2008). A comprehensive description can be found in Wirsenius (2000, pp. 13–54). Please note that the model described in those publications refers to a previous and less comprehensive version, named the Food Phytomass Demand model. The major difference between the model versions is that, in contrast to the previous ones, the version used in this study includes explicit representation of land use.

3. Scenario rationale, data and methodological approach

3.1. Overview of scenarios and methodological approach

This section describes the scenarios and their rationale, with details on parameter values, data sources, and modeling methodology. For more comprehensive details on input and output data see Wirsenius (2008). See Table 1 for a brief description of the main characteristics of each of the four scenarios.

The "Reference" scenario (REF) is a physical representation of the FAO projections for 2030 (Bruinsma, 2003), in terms of total agricultural land use and total biomass production and use. As that study did not include projections of total feed use or total agricultural land use, REF complements the FAO projections with estimates of these parameters. In order to make these estimates as consistent as possible with the FAO projections, we used all available and applicable data in the projections to calibrate the model calculations for this scenario.

The scenario "Increased Livestock Productivity" (ILP) is based on REF, but the productivity and feed use of the livestock sector is different. In this scenario, we assumed faster growth of livestock productivity and feed-to-food efficiency (defined here as amount of animal food produced per amount of feed eaten). The principal rationale of this scenario was that the FAO assumptions on increases in livestock productivity may be considered relatively low. Furthermore, emerging factors might promote faster growth in productivity, especially increased competition for land from the growing bioenergy sector, and stricter climate and environmental policies related to land use and the livestock sector (see further Section 5.4).

The scenario "Ruminant Meat Substitution" (RMS) is based on ILP, but with some modifications of the per-capita consumption of different meat types. In this scenario, 20% of the per-capita consumption of ruminant meat (beef and mutton) in REF and ILP is replaced by an equal amount (in terms of kg $capita^{-1}$ $year^{-1}$) of pork and poultry, with the same proportions of pork and poultry as in REF and ILP. The rationale for this scenario is that ruminant meat is by far the most feed and land-demanding meat product, and even relatively small reductions in consumption levels have significant effects on total land use. Several upcoming factors may moderate ruminant meat consumption, such as increases in land and feed prices, as well as climate and environment policy-induced price increases on meat (see further Section 5.2).

The scenario "Minor Vegetarian Transition and Less Food Wastage" (MVT) is based on RMS, with the addition of (i) a partial substitution of (mainly) vegetable food for meat, and/or (ii) a decrease in food wastage at retail and household levels. This scenario was only applied to regions with high per-capita meat consumption and/or high degree of food wastage. One rationale for assuming a partial shift from meat to vegetable food is the increasing importance people attach to health and ethical aspects in relation to food consumption. Substitution of vegetable food for meat may also be realized by greater incorporation of vegetable food in minced and processed meat products (see further Section 5.2). Food wastage is generally higher in regions with higher per-capita incomes. However, levels vary greatly between countries with the same income levels, suggesting a potential for decreasing food wastage in medium and high-income regions (Bender, 1994).

3.2. Food use and population

For population numbers and values for a selection of major food use parameters in the scenarios, see Table 2. In this study, the concept of "food end-use" is used instead of the common term "consumption", in order to stress that, in general, what is referred to as "consumption" in national statistics and similar in reality is not the amount of food eaten but the amount of the food supplied on the wholesale level. To distinguish between this and the food eaten, the concept "food intake" is used to represent the amount of food actually eaten. The ratio between "intake" and "end-use" is defined as "food end-use efficiency".

Table 1
Main characteristics of scenarios in 2030. Note that only a limited number of the feedstuff categories were included in the projections in Bruinsma (2003) (for further details, see text and Table 5), and that projections of future yield of forage crops (grasses, legumes, etc.), and yield and grazing intake on pastures, were not included in Bruinsma (2003). Also note that pasture intake per ha are somewhat lower in ILP, RMS, and MVT compared with REF (for further details see text and Table 6).

Scenario and scenario abbreviation	Total food end-use and food intake	Shares of vegetable and animal products in diets	Livestock productivity	Livestock feed ration	Crop and pasture productivity	Trade of crops, feed and food products
"Reference" (REF)	As in Bruinsma (2003)	As in Bruinsma (2003)	Adapted to data in Bruinsma (2003)	Adapted to data in Bruinsma (2003) (where applicable)	As in Bruinsma (2003) (where applicable)	As in Bruinsma (2003)
"Increased livestock productivity" (ILP)	As in REF	As in REF	Higher annual increases in productivity	Adjusted for increased livestock productivity (higher energy and protein content of feed)	As in REF	Feedstuff: adjusted for changed use, esp. of oil meals. Food products: As in REF
"Ruminant Meat Substitution" (RMS)	As in REF	20% of ruminant meat per capita use is substituted with pork and/or poultry meat	As in ILP	As in ILP	As in REF	As in ILP
"Minor Vegetarian Transition and Less Food Wastage" (MVT)	In regions where food end-use eff. is below 70% in the REF scenario, the value is increased up to 10%, to a maximum level of 70%. Amount protein no less than 70 g $capita^{-1}$ $year^{-1}$	Pulses, vegetables and fruits increased, and (mainly) meat decreased. Total meat decrease up to 25%, to a minimum level of 70 kg $capita^{-1}$ $year^{-1}$	As in ILP	As in ILP	As in REF	As in ILP

Note: This scenario applies mainly to W. Europe and North America and Oceania.

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For REF and ILP, food end-use was calibrated against corresponding values of food consumption in Bruinsma (2003), whereas numbers on food end-use efficiency were based on previous estimates by Wirsenius (2000, 2003a,b). For RMS, values were based on REF/ILP, and for MVT, values were based on RMS – in both cases with the modifications described in Section 3.1.

The modified values in the MVT scenario were applied only to those regions where total meat end-use exceeds 70 kg capita^{-1} year^{-1}, and/or food end-use efficiency is below 70% in the REF scenario. In these regions (East Europe, North America and Oceania, Latin America, and West Europe), food end-use was changed relative to the RMS scenario, assuming: (i) a partial substitution of pulses, vegetables, fruits, and dairy products/eggs for meat, and (ii) an increase in food end-use efficiency. The assumed magnitude of these changes was constrained by these rules:

Table 2
Population and selected values on food end-use and food end-use efficiency in the scenarios for 2030. Data for 1992/1994 from Wirsenius (2000, 2003a,b), and those for 1997/1999 from Bruinsma (2003).

Parameter	Year/scenario	World	East Asia	East Europe	Latin America and the Caribbean	North Africa and West Asia	NorthAmerica and Oceania	South and Central Asia	Sub-Saharan Africa	West Europe
Population (million)	1997/1999	5867	1966	340	497	382	330	1350	614	388
	2030	8226	2424	290	715	633	425	2093	1267	380
Total food end-use per-capita (MJ ME capita^{-1} day^{-1})[a]	1992/1994	11.4	11.4	13.2	11.5	12.5	14.7	9.9	9.1	14.2
	REF/ILP/RMS	12.8	13.3	14.3	13.1	13.6	15.5	12.2	10.7	14.7
	MVT	12.7	13.3	13.5	13.1	13.6	14.1	12.2	10.7	13.4
Food end-use efficiency (ME basis)	1992/1994	73%	74%	70%	76%	72%	63%	81%	87%	66%
	REF/ILP/RMS	68%	70%	65%	71%	69%	60%	73%	80%	63%
	MVT	71%	70%	70%	71%	69%	66%	73%	80%	70%
Total meat end-use per-capita (kg fresh weight capita^{-1} year^{-1})	1997/1999	36.4	38.0	50.3	53.8	22.1	117	6.4	11.0	86.3
	REF/ILP/RMS	45.3	58.6	67.6	76.6	36.5	122	12.9	14.6	96.2
	MVT	42.2	58.6	63.5	70.0	36.5	91.5	12.9	14.6	72.5
Ruminant meat end-use per-capita (kg fresh weight capita^{-1} year^{-1})	1997/1999	11.6	5.6	16.1	25.3	11.2	44.0	5.0	7.3	22.8
	REF/ILP	13.0	9.5	20.5	29.0	14.3	36.7	6.7	8.7	21.4
	RMS	10.4	7.6	16.4	23.2	11.4	29.3	5.4	6.9	17.0
	MVT	9.7	7.6	15.4	21.2	14.3	22.1	5.4	6.9	12.9
Fruit and vegetables (kg fresh weight eq. capita^{-1} year^{-1})	1997/1999	157	186	157	140	237	249	84.7	63.0	280
	REF/ILP/RMS	171	221	193	158	248	289	102	71.4	320
	MVT	179	221	183	158	248	365	102	71.4	385

[a] 1 MJ = 239 kcal. ME: Metabolizable energy.

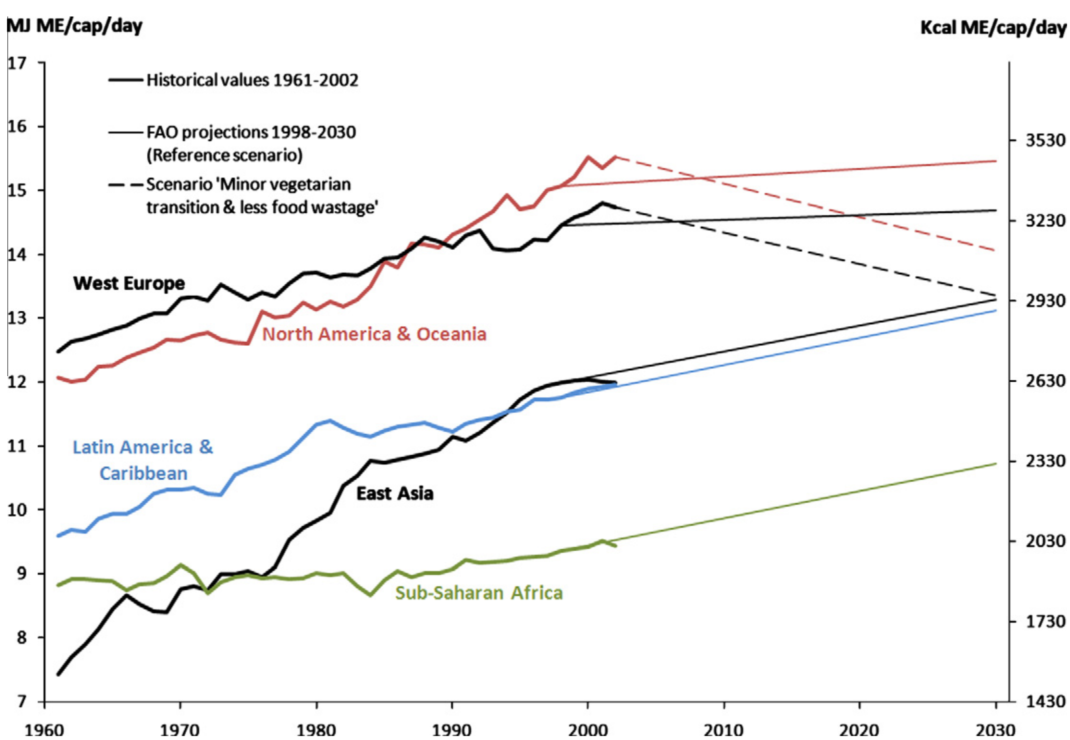

Fig. 1. Total food end-use per-capita for a selection of high-income and low-income regions. Note that for scenario 'Minor Vegetarian Transition and Less Food Wastage', values are different from those of the 'Reference' scenario only for the regions West Europe, East Europe and North America and Oceania. ME: metabolizable energy. Historical data from FAOSTAT; FAO projections from Bruinsma (2003).

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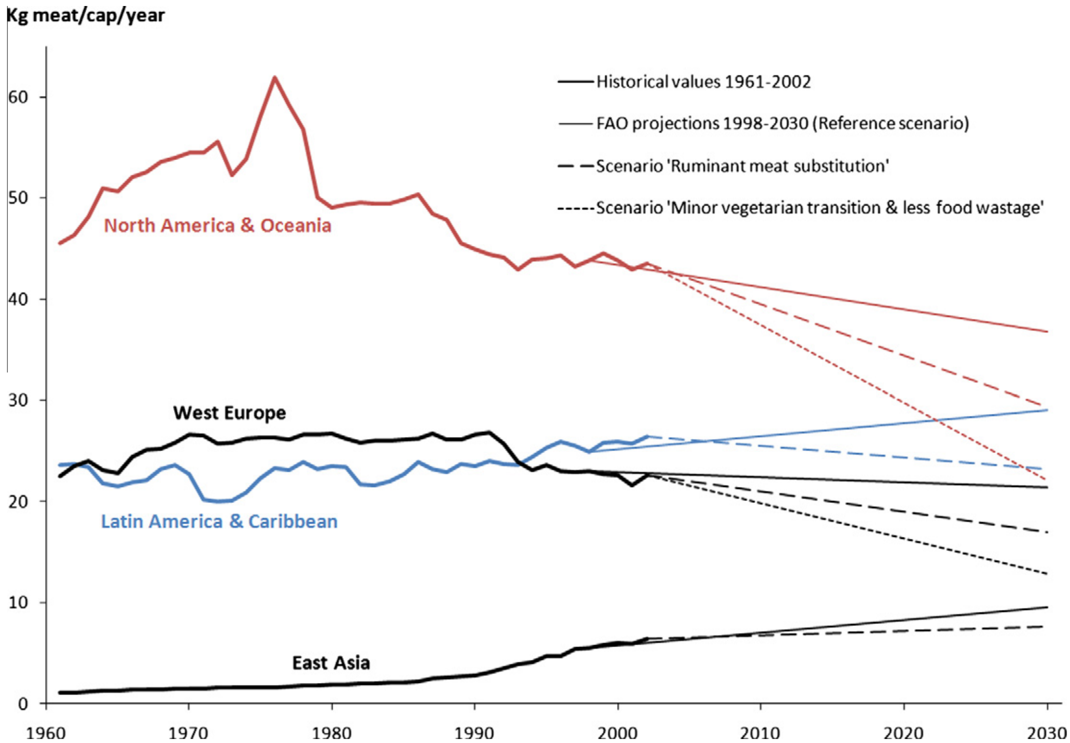

Fig. 2. Ruminant meat (beef, mutton) end-use per-capita for a selection of high-income and low-income regions. Historical data from FAOSTAT; FAO projections from Bruinsma (2003).

- Meat end-use is reduced by at most 25%, but should never fall below 70 kg cap^{-1} $year^{-1}$, which, for a point of reference, is the same level as the average consumption in the EU15 in the early 1970s, or in the UK in 2000.
- Pulses, vegetables, and fruit end-use is increased by at most 25% (for the sum of pulses, vegetables and fruit, by weight).
- Protein intake should not fall below 70 g cap^{-1} day^{-1}, and fat intake should not exceed 30% of total energy (ME) intake. These numbers are based on recommendations for nutritionally adequate and healthy diets (WHO, 1985; HHS/USDA, 2005).
- If the share of animal food in the diet was less than 25% (in energy terms) in the REF/ILP/RMS scenarios, meat was replaced only by other types of animal food (dairy products, eggs); if the share was more than 25%, meat was replaced by both vegetable and other animal food.
- Food end-use efficiency is increased by at most 10%, but should never exceed 70%, which is a level found in many affluent countries, including Australia, Finland and Spain, and below the best practice in high-income countries of about 75% (Japan, Sweden, Switzerland).

Figs. 1 and 2 show comparisons between major food end-use values in the scenarios and historical trends since the early 1960s. Fig. 1 shows that the assumed higher end-use efficiency in MVT would imply a clear reversal of current trends in North America and Oceania and West Europe. In both regions, end-use per-capita continues to rise – mainly due to a continued increase in food wastage – and has already reached the level projected by the FAO for 2030.

3.3. Livestock productivity and feed energy requirements

For aggregated productivity of animal food production, expressed as production-per-head and year in REF and ILP/RMS/MVT, see Table 3. Table 4 shows livestock productivity in the scenarios expressed in terms of feed use per unit of food, for the feed rations as determined in the model calculations (see Section 3.4). The feed per product numbers in Table 4 should primarily be used for comparisons over time, within each region and system. Comparisons of feed-to-food efficiency between different animal food systems and regions should be made with great caution, taking into account that type and nutritional quality of feedstuffs vary substantially, as do the energy and water content of the product output (e.g. water content of milk is ~90% and for carcass ~55–60%). For a more accurate comparison between different animal food systems from a feed energy conversion point of view, see Fig. 3.

In REF, for each animal system and region, values for animal base parameters (live weight, live-weight gain, reproduction rate, milk/egg production rate, etc.) in the ALBIO model were adjusted so that the model values at the aggregated level for offtake, carcass weights and production-per-head agreed with Bruinsma (2003). These base parameter values were adjusted within the ranges assumed to be appropriate for each region, using estimates in Wirsenius (2000, 2003a,b) for reference. Base parameter values are available in Wirsenius (2008).

The higher productivity levels in the ILP scenario were based on assumptions of faster growth in livestock productivity. Few studies have analyzed potential long-term growth in livestock productivity on a country-wide or larger scale – some of these include Winrock International (1992), Simpson et al. (1994), SNV (1997), Delgado et al. (1999). Therefore, the assumed productivity levels were mainly a result of analysis in this study, based on a number of factors, including:

- Agronomic/biological potentials – in terms of e.g. milk yield, reproduction rates, live-weight gain rates, etc. – using empirical data from top-performing countries as points of reference.
- Expected growth in GDP per-capita to 2030 in each region (data from Bruinsma (2003). In general, a higher GDP growth was taken as a basis for assuming higher growth rates in livestock productivity overall.

Table 3
Productivity of major livestock groups, expressed as production-per-head and year, in the scenarios for 2030 and historical trends during 1961–2005. The model values on animal base parameters in the ILP scenario were applied also in the RMS and MVT scenarios. All weight numbers are given in fresh weight. Data for 1961–2005 from FAOSTAT.

Animal system and parameter	Historical growth/scenario values	World average	East Asia	East Europe	Latin America and the Caribbean	North Africa and West Asia	North America and Oceania	South and Central Asia	Sub-Saharan Africa	West Europe
Cattle and buffalo carcass production (kg head^{-1} year^{-1})	Annual growth 1961–2005	0.9%	3.8%	1.6%	0.6%	2.3%	1.0%	2.2%	0.2%	0.8%
	REF scen. (FAO projections)	47.7	55.8	70.0	46.5	62.0	115	21.4	24.4	111
	An. growth fr. 1997/1999	0.6%	1.3%	0.2%	0.7%	1.0%	0.2%	1.6%	1.7%	0.6%
	ILP scenario	63.3	71.2	90.0	73.5	74.4	140	29.5	27.5	131
	An. growth fr. 1997/1999	1.5%	2.1%	1.0%	2.1%	1.6%	0.8%	2.6%	2.1%	1.1%
Cattle and buffalo milk production (kg dairy cows^{-1} year^{-1})	Annual growth 1961–2005	0.5%	2.2%	1.5%	0.7%	1.0%	1.9%	1.5%	−0.4%	1.8%
	REF scen. (FAO projections)	2130	1970	3210	1730	1970	7040	1590	535	5980
	An. growth fr. 1997/1999	0.2%	0.8%	0.6%	0.5%	1.1%	0.3%	0.9%	0.8%	0.2%
	ILP scenario	4060	4340	5990	3250	3450	11,000	3220	1000	10,000
	An. growth fr. 1997/1999	2.2%	3.3%	2.6%	2.5%	2.9%	1.7%	3.2%	2.8%	1.8%
Sheep and goats carcass production (kg head^{-1} year^{-1})	Annual growth 1961–2005	1.0%	4.6%	0.6%	0.8%	1.0%	0.7%	0.7%	0.3%	0.6%
	REF scen. (FAO projections)	8.7	10.5	10.6	4.4	9.7	10.9	8.4	6.7	10.0
	An. growth fr. 1997/1999	1.1%	0.9%	0.7%	0.8%	1.1%	1.0%	1.4%	1.8%	0.3%
	ILP scenario	10.6	12.5	12.3	6.4	11.8	13.0	10.5	7.9	12.2
	An. growth fr. 1997/1999	1.7%	1.4%	1.2%	2.0%	1.7%	1.5%	2.1%	2.3%	1.0%
Pig crude carcass production (kg head^{-1} year^{-1})	Annual growth 1961–2005	1.3%	3.3%	0.9%	2.2%	–	1.1%	1.0%	0.1%	0.8%
	REF scen. (FAO projections)	117	120	104	71.9	–	158	74.9	55.8	149
	An. growth fr. 1997/1999	0.5%	0.7%	0.2%	1.0%	–	0.4%	2.1%	1.9%	0.1%
	ILP scenario	152	160	141	116	–	170	84.5	60.9	170
	An. growth fr. 1997/1999	1.3%	1.6%	1.2%	2.5%	–	0.7%	2.5%	2.2%	0.5%
Poultry carcass production (kg head^{-1} year^{-1})	Annual growth 1961–2005	1.7%	1.8%	2.4%	3.3%	1.1%	1.7%	3.2%	1.7%	2.9%
	REF scen. (FAO projections)	5.8	4.2	4.6	7.2	5.6	11.5	4.7	3.2	8.8
	An. growth fr. 1997/1999	1.1%	1.4%	1.1%	1.2%	1.9%	1.0%	3.7%	1.9%	0.5%
	ILP scenario	7.8	6.4	6.5	9.7	7.5	13.1	5.2	3.9	10.4
	An. growth fr. 1997/1999	2.0%	2.8%	2.2%	2.1%	2.8%	1.5%	4.1%	2.5%	1.0%

Table 4
Feed use per produced food unit for major livestock systems in the REF and ILP scenarios in 2030. All numbers are given in dry weight of feed intake per fresh weight of product generated. Feed use here refers to the feed eaten by all animal categories in each animal food system (i.e. adult animals, animals reared for replacing adult animals, and animals reared for meat production). Meat refers to produced amount of whole carcass from all animal categories (i.e. carcass from culled adult animals and animals reared specifically for meat production). Note that for milk systems, feed use includes feed eaten by both milk cows and replacement heifers; product output includes whole-milk as well as carcass of culled cows. Data for 1992/1994 from Wirsenius (2000, 2003a,b).

Animal system and parameter	Scenario	World average	East Asia	East Europe	Latin America and the Caribbean	North Africa and West Asia	North America and Oceania	South and Central Asia	Sub-Saharan Africa	West Europe
Cattle whole-milk	1992/1994	2.5	2.9	2.1	3.9	3.8	1.2	4.4	9.0	1.4
	REF	2.4	2.2	1.7	3.1	2.3	1.1	3.6	7.1	1.2
	ILP	1.6	1.4	1.3	1.9	1.9	0.9	2.1	4.3	1.0
Buffalo whole-milk	1992/1994	4.2	8.3	–	–	4.5	–	3.9	–	–
	REF	3.2	5.6	–	–	3.0	–	3.0	–	–
	ILP	2.3	3.6	–	–	2.3	–	2.2	–	–
Beef cattle meat	1992/1994	59	108	38	85	101	27	241	130	27
	REF	50	49	36	64	48	24	146	102	26
	ILP	43	38	34	44	37	23	128	98	24
Sheep meat	1992/1994	76	83	59	136	68	68	86	124	45
	REF	53	50	38	99	44	41	58	79	43
	ILP	45	39	39	79	39	37	43	69	39
Pork (crude carcass)	1992/1994	5.3	6.2	4.6	8.6	–	3.7	8.3	9.7	3.9
	REF	4.3	4.3	4.2	6.1	–	3.5	6.0	8.1	3.6
	ILP	3.5	3.4	3.6	4.2	–	3.3	5.1	7.4	3.3
Egg	1992/1994	2.9	3.0	3.0	2.7	3.3	2.3	3.9	4.1	2.3
	REF	2.7	2.5	2.7	2.8	2.7	2.3	2.7	4.7	2.3
	ILP	2.4	2.3	2.4	2.4	2.6	2.2	2.7	3.9	2.2
Poultry meat	1992/1994	3.5	4.1	3.9	3.6	4.4	2.9	5.2	5.6	2.7
	REF	3.3	4.0	3.2	3.1	3.4	2.7	3.4	3.3	2.8
	ILP	2.6	2.6	2.6	2.5	2.9	2.5	3.0	3.2	2.5

- Historic (since 1961) rates of productivity growth for each animal food system and region (data from FAOSTAT). These trends, with particular emphasis on the most recent 10–20 years, were used as an additional guideline for future productivity growth rates.
- Current levels of production-per-head and animal base parameter (live weight, live-weight gain, reproduction rate, milk/egg production rate, etc.) values. In general, low values were taken as a basis for accepting higher growth rates, if other factors (e.g. GDP outlook, trends) pointed in that direction.

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The assumed productivity values in ILP, and the corresponding values in the FAO projections (i.e. REF), are illustrated in a historical perspective for the two major ruminant systems and regions in Figs. 4 and 5.

3.4. Livestock feed rations

Feed rations were determined under several exogenous and endogenous constraints, structured in sets of decision rules (Table 5) which were applied as consistently as possible. Since feed

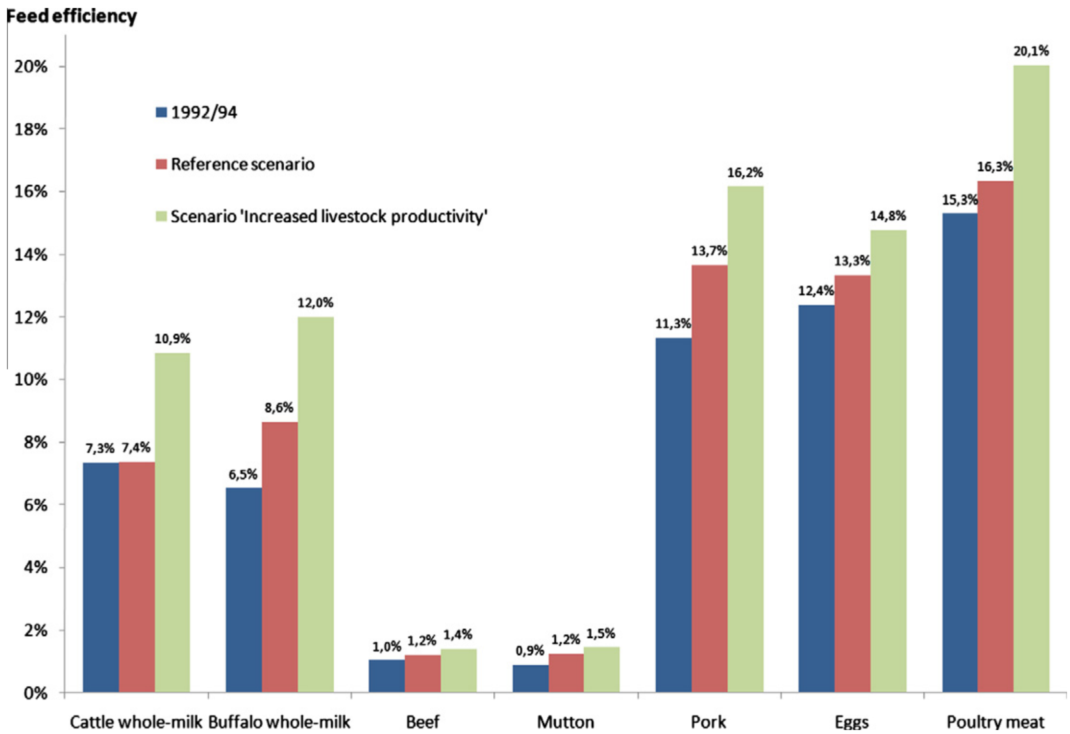

Fig. 3. Global averages of feed-to-food efficiency for major livestock systems in 1992/1994 and in scenarios for 2030. Feed efficiency is calculated as gross energy content of product output, divided by gross energy content of feed eaten. Data for 1992/1994 from Wirsenius (2000, 2003a,b).

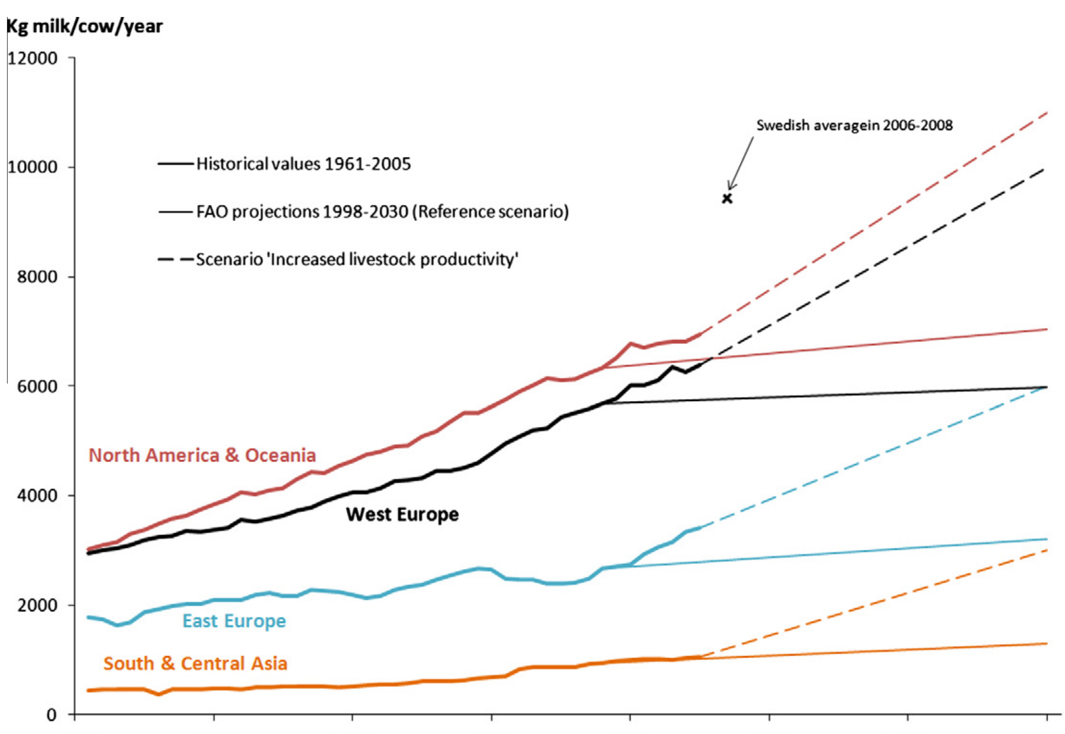

Fig. 4. Productivity of cattle milk production in major dairy regions, expressed as cattle whole-milk production per number of milk cows ('milk yield'). Historical data from FAOSTAT; FAO projections from Bruinsma (2003); data for Sweden from Swedish Dairy Association (2010).

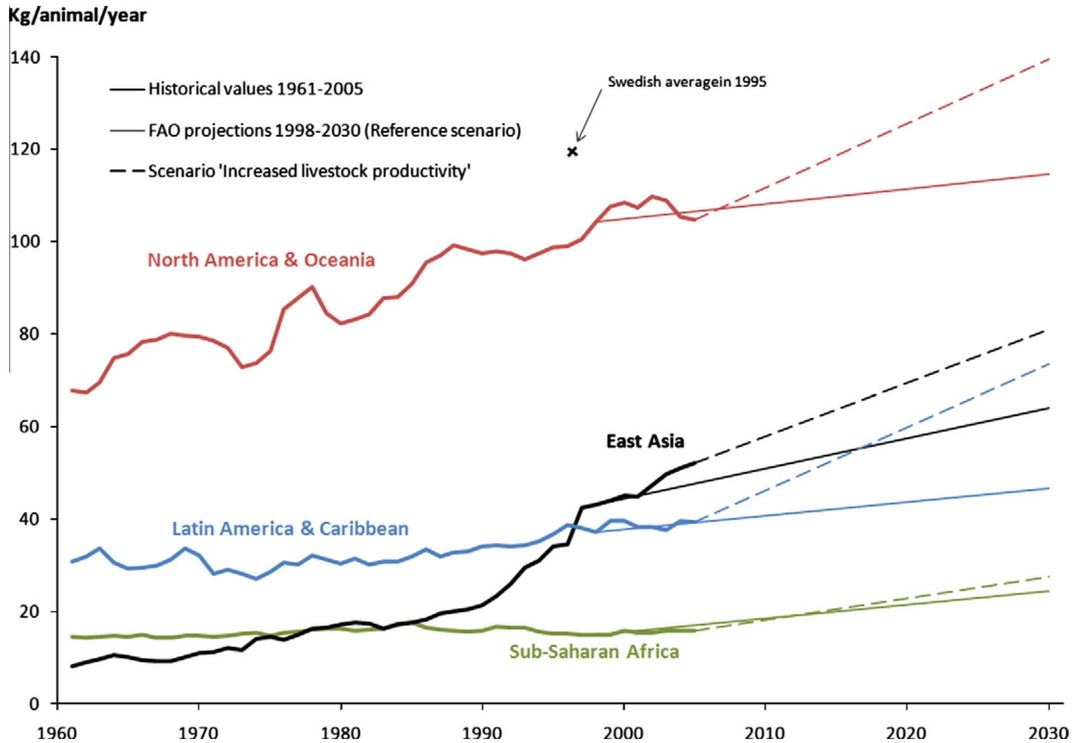

Fig. 5. Productivity of cattle meat production in some major beef producing regions, expressed as cattle carcass production per total number of cattle. Note that since this parameter is the average for both dairy and beef cattle, differences in absolute value are not only due to differences in meat productivity, but also to differences in the relative numbers of dairy and beef cattle. Historical data from FAOSTAT; FAO projections from Bruinsma (2003); data for Sweden from SNV (1997).

rations essentially were determined endogenously, and therefore considered an outcome of, rather than input to, the model calculations, the feed rations as such are presented in the results section.

In REF, for categories for which explicit data on feed use were included in Bruinsma (2003) – mainly cereals, starchy roots, oil crops, and pulses – feed use numbers in REF were set equal to the 2030 feed use numbers in Bruinsma (2003). For animal forage crops and cropland pasture no numbers on feed use were included in Bruinsma (2003). However, it did include data on harvested area for animal forages and some other minor crops, in one single category ''other land''. Therefore, use of forage crops and cropland pasture in REF were estimated by matching the harvested area of these crops with that of ''other land'' in Bruinsma (2003).

For all other feed categories, permanent pasture, browse (non-herbaceous plant matter, e.g. twigs), and various by-products and residues from crop production and food industry – which in total currently cover about 65% of the feed energy needed by livestock globally – no data were included in Bruinsma (2003). Feed energy requirements remaining, after the Bruinsma (2003) categories had been accounted for, were allotted to permanent pasture and browse and by-products and residues, where the chosen distribution between them in each region depended on i) present extent of the use of these feedstuffs and ii) estimated availability of by-products and residues for use as feed in 2030. For food industry by-products of high nutritive value (e.g. oil meals) use as feed was assumed to be limited mainly by availability, and around 80–90% of produced amounts were assumed to be used as feed. For fibrous crop residues (e.g. straw), use as feed was in most regions assumed to be limited by their generally low nutritional value. In total, these assumptions meant that by-products and residues in all regions contributed to substantial shares of the feed energy requirements. However, due to either limited availability or poor nutritional value of by-products and residues, grazed pasture and browse had to cover the greater part of the remaining feed energy requirements. Due to the large increases in ruminant numbers projected in Bruinsma (2003) for all regions except North America and Oceania and Europe, this implied vast increases compared to current levels in required intake of pasture and browse except in these regions.

In ILP, RMS and MVT, feed rations were determined mainly from the nutritive quality of feed rations that could be deemed required for attaining the assumed livestock productivities, which were overall higher than in REF. This means that for each animal category, the feed ration formulation was guided by specified energy and protein densities considered necessary for achieving the productivity targets. For assumed values of the nutrient density requirements, see Wirsenius (2008). Besides these nutrient density requirements, other factors for determining feed rations were the extent of permanent pasture resources in each region and the availability of by-products and residues for use as feed. Use of by-products and residues was, as a general rule, maximized under the constraints of their regional availability and the defined nutrient density requirements. Similar to in REF, use of protein and energy-rich food industry by-products as feed was limited only by their availability – about 80–90% of available amounts were used as feed. For fibrous crop residues, use as feed was to a greater extent than in REF restricted by low nutritional value, since livestock productivities, and consequently the energy density requirements of the feed rations, were higher in these scenarios.

3.5. Crop and permanent pasture yields

Table 6 presents crop and pasture productivity numbers used in the scenarios, for a selection of crops and pasture types. For crops for which data on yields per unit area were included in Bruinsma (2003) – essentially all major edible-type crops – yield numbers in REF equaled those in Bruinsma (2003). In ILP, RMS and MVT,

Table 5
Summary of major decision rules for determining feed rations in scenarios. Note that "physical" availability refers to total amount produced, whereas "economic" availability in addition takes into account factors impeding usage (e.g. long transport distances) and competing uses. Feed categories not shown in table include fibrous food industry by-products (bagasse, rice hulls), meat and bone meal, fish meal and food waste. In REF, their share of total feed use amounted to 1.6% (in metabolizable energy terms).

Feed categories	Reference scenario major determining/limiting parameter (in order of importance)	Comment	All other scenarios major determining/limiting parameter (in order of importance)	Comment
Products				
Concentrates (cereals, starchy roots, oil crops and pulses)	1. Amount used as feed according to 2030 projections in Bruinsma (2003)	Total use for each crop and in each region was calibrated against feed use data in Bruinsma (2003).	1. Energy and protein density of feed ration	Use of concentrates was minimized under nutrient density requirements
Forage crops (grass, etc.) and cropland pasture	1. Area according to 2030 projections in Bruinsma (2003)	Harvested area in each region was calibrated against Bruinsma (2003) data.	1. Energy and protein density of feed ration	Use of forage crops was minimized, but preferred to concentrates, under nutrient req.
Permanent pasture and browse	1. Feed rations in 1992/1994 2. Estimated feed energy balance in 2030		1. Share grazed feed (perm. and cropl. pasture, and non-agric.) in feedmix within defined interval	
By-products and residues				
Fibrous crop residues	1. Physical availability 2. Low nutritional value 3. Economic availability	Availability was restricted by residues left in-field (in total ~21% of gener.) and use for bedding in animal confinements (~10% of gener.).	1. Energy density of feed ration 2. Physical availability	Use of fibrous residues was maximized; was in most regions limited by energy density requirements.
Non-fibrous crop residues (potato tops, etc.)	1. Physical availability 2. Economic availability		1. Physical availability 2. Economic availability	Use of non-fibrous crop residues and food industry by-products was maximized; was limited only by availability
Non-fibrous cereal, sugar and beverage industry by-prod.	1. Physical availability (~83% of generated was used)		1. Physical availability	
Oil meals (including cotton meal)	1. Physical availability (~88% of generated was used globally)	Use allocated to livestock categories with higher protein requirements. Trade between regions if surplus or deficit.	1. Physical availability 2. Protein density of feed ration	Use was maximized. Allocation and trade similar to procedure in reference scenario.
Non-agricultural herbage and browse (scavenging, roadside/forest grazing)	1. Economic availability 2. Physical availability		1. Economic availability 2. Physical availability	Fixed value for each animal category in each region.

Table 6
Selected values on major productivity parameters for crop production and grazing in 2030 (averages for rainfed and irrigated production). All yield numbers, pasture intake, and amount crop residues left in-field are in Mg dry matter ha^{-1} $year^{-1}$. Harvest index refers to the share of harvested product (e.g. grains) out of total above-ground production; except for underground crops, where harvest index refers to share out of whole-plant production (on dry matter basis). Pasture utilization values refer to eaten plant mass by livestock as share of the above-ground growth of edible plant mass (on dry matter basis, annually). Estimates for 1992/1994 from Wirsenius (2000, 2003a,b).

Crop/pasture system	Parameter	Scenario	World average	East Asia	East Europe	Latin America	North Africa and West Asia	North America and Oceania	South and Central Asia	Sub-Saharan Africa	West Europe
Wheat	Grain yield	All	3.0	3.8	2.2	3.0	2.3	2.6	2.8	2.2	6.9
	Harvest index	All	48%	50%	45%	47.5%	45%	50%	45%	37.5%	55%
	Straw left in-field	All	0.9	1.1	0.9	1.0	0.9	1.0	0.3	0.7	1.7
Rice (paddy)	Grain yield	All	4.2	4.6	2.6	4.3	6.1	7.2	3.7	2.4	6.7
	Harvest index	All	55%	57.5%	47.5%	55%	57.5%	57.5%	52.5%	45%	57.5%
	Straw left in-field	All	0.8	1.0	0.9	1.0	1.3	1.6	0.5	0.6	1.5
Maize	Grain yield	All	4.7	4.5	4.0	3.7	5.6	9.7	2.4	1.8	9.8
	Harvest index	All	43%	40%	40%	37.5%	45%	55%	32.5%	27.5%	55%
	Straw left in-field	All	1.2	1.4	1.2	1.2	1.4	1.6	0.5	0.7	1.6
Cassava	Tuber yield	All	4.4	5.2	–	5.2	–	–	8.3	4.1	–
	Harvest index	All	56%	57.5%	–	57.5%	–	–	62.5%	55%	–
Soybean	Grain yield	All	3.1	2.1	–	3.0	–	4.6	1.6	1.4	4.2
	Harvest index	All	53%	50%	–	52.5%	–	55%	47.5%	45%	52.5%
	Straw left in-field	All	0.8	0.8	–	0.9	–	1.1	0.2	0.3	1.1
Sugar cane	Stem yield	All	25	24	–	24	32	30	28	21	–
	Harvest index	All	70%	70%	–	70%	72.5%	70%	70%	65%	–
	Leaves left in-field	All	1.4	1.3	–	1.3	1.5	1.6	1.2	1.4	–
Veg, fruits, pulses	Average yield	All	1.6	1.9	1.0	1.7	2.2	3.0	1.4	0.9	2.2
Grass legume	Total yield	All	6.7	9.9	4.0	6.8	6.0	4.8	10	5.6	8.3
Cropland pasture	Total yield	All	4.5	6.8	3.4	5.5	3.6	4.0	6.4	–	7.1
	Pasture utilization	All	65%	65%	65%	65%	65%	65%	65%	–	65%
Permanent pasture	Plant mass grazed (intake) per ha	1922/1994	0.68	0.62	1.3	1.3	0.29	0.35	1.1	0.43	1.8
		REF	1.00	1.12	1.3	1.6	0.42	0.35	2.0	0.70	1.8
		ILP	0.89	1.02	1.3	1.5	0.41	0.35	1.6	0.69	1.8
		RMS	0.86	0.95	1.3	1.4	0.40	0.35	1.5	0.68	1.8
		MVT	0.86	0.95	1.3	1.4	0.40	0.35	1.5	0.68	1.8

yield numbers of these crops were assumed to be the same as in REF. Since cropland areas in those scenarios are smaller than REF, it might be reasonable to assume higher yields, since smaller areas are used and marginal productivity in general drops with acreage, i.e., the marginal productivity of additional agricultural land in general is lower than the average productivity. However, in order to obtain conservative estimates of the land savings in those scenarios we chose to assume the same cropland yields as in REF.

For animal forage crops and cropland pasture, yields were estimated from a combination of various data sources and their total area resulting from the feed ration calculations. Since Bruinsma (2003) gives total harvested area for these crops, yield assumptions could be checked against the harvested area obtained in the model. By simultaneously tuning yields and shares in feed rations against resulting land area and literature data on yields, a best possible match was aimed at for each region.

Except for cropland in REF, all other land area numbers were an outcome of this study, see Section 4. In REF, numbers on cropland area and cropping intensity equaled those in Bruinsma (2003). The same cropping intensity numbers were used in the calculations of cropland area requirements in all other scenarios.

Harvest index numbers were of crucial importance in the scenario calculations, since they determine the amount of crop residues produced for a given crop production level. Numbers in this study were largely based on previous analyses of harvest index numbers at global and regional levels (Wirsenius, 2000, 2003a,b). Amount of crop residues left in-field after harvest were mainly based on assumptions on predominating harvesting practices for different crops and regions. In regions where manual harvesting is significant and/or where substantial use of crops residues for feed/fuel takes place (including in-field grazing of residues), shares of uncut (or non-grazed) straw were assumed to be low. This applied particularly to South and Central Asia.

For permanent pasture, no data on productivity, intensity in use (pasture intake per ha), or area were included in Bruinsma (2003). Despite the immense importance of permanent pastures in ruminant production, there is startlingly little data available at region-wide levels of their productivity or intensity in use. Therefore, numbers on pasture intake per ha were estimates of this study, based on the estimated required pasture consumption (see Section 3.4), estimates of current pasture intake per ha (Wirsenius, 2000) and current permanent pasture areas (FAOSTAT). Assumed changes as compared to present were based on region-specific assumptions on constraints for expansion of area and/or increase of pasture intake per ha, as well as a general assumption that land-use intensity in ruminant production will increase (see Section 5.4 for possible factors behind increased land-use intensity).

For the region-specific assumptions, the low and medium-income regions assumed to have the strongest constraints in area expansion included East Asia, North Africa and West Asia and South and Central Asia, since in those regions current agricultural land area already represents a large share of potential (i.e. agronomically suitable) agricultural area (Bruinsma, 2003). For the same reason, constraints were assumed to be less severe in Latin America and Sub-Saharan Africa, where current agricultural area represents a relatively small share of potential area (Bruinsma, 2003). As mentioned in Section 3.4, in all low and medium-income regions in REF, vast increases in pasture intake as compared to in 1992/1994 were necessary to meet estimated feed energy requirements. In the most land-constrained regions, most of these increases were assumed to be met through higher intensity;

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pasture intake per unit area increased by up to 80% in these regions, whereas expansions in permanent pasture area were assumed to be about 5–10% (see Table 6 and Supplementary material).

The feasibility of the large increases in pasture intake per ha in REF can be questioned. Therefore, in ILP, RMS and MVT, where increased livestock productivity implied that required total pasture intake was much less than in REF, we assumed lower increases in pasture intake per ha. Despite the lower yields compared to REF, resulting total permanent pasture areas are smaller than at present in those scenarios. It could be argued that yields in ILP, RMS and MVT should be higher, instead of lower, than in REF, since smaller areas are used and, assuming that, as mentioned above, marginal productivity drops with acreage. However, one could also argue that yield levels might be lower in the scenarios with decreasing permanent pasture areas, since land values might be lower than in REF, which would make high land-use intensity less profitable. In this study, we chose to assume somewhat lower yields, in order to obtain conservative estimates of the land savings in ILP, RMS and MVT.

3.6. Trade

In REF, trade of crops and food commodities between regions equals the corresponding values in Bruinsma (2003). In all other scenarios, net-imports as share of domestic supply were essentially the same as in REF for all flows except cereals and oil crops where minor deviations in trade numbers were made in response to the changed domestic use of feed in these scenarios.

For oil meals – which currently account for about two thirds of the global supply of high-protein feedstuffs and of which intercontinental trade is significant – no trade data were included in Bruinsma (2003). Trade flows of oil meals were therefore estimated from modeled data, calibrated against data on vegetable oils production in Bruinsma (2003). The ALBIO model calculates endogenously the produced amount of oil meals as a function of oil yield and oil production in each region – the latter was calibrated against data in Bruinsma (2003), giving a reasonable accurate estimate of regional oil meal supply. Since the model also calculates the feed protein requirements in each region, estimates of oil meals trade flows could be based on the balance of supply of and demand for feed protein in each region.

Hence, in all scenarios, trade of oil meals was mainly determined as an outcome from the balance in each region between estimated domestic supply of feed protein in oil meals and estimated domestic feed protein requirements in livestock production. Essentially, regions with feed protein surplus (mainly Latin America and North America and Oceania) were allowed to export this to regions with deficits (mainly East Asia and West Europe). Trade numbers in all scenarios are given in Wirsenius (2008).

4. Scenario results

This section presents results from the scenarios, with focus on feed use and land requirements. Figs. 6–10 summarize some of the major results; Table 7 provides an overview of the changes from 1993 to 2030 of major factors determining land requirements for animal food. More detailed numbers on feed and land use, including regional data, are given in the Supplementary material.

4.1. Feed and land use in the reference scenario

Feed use in REF is considerably larger than current levels (Fig. 6), mainly due to the large increases in livestock numbers assumed in Bruinsma (2003) (Table 7). Feed types not accounted for in Bruinsma (2003) make up nearly 80% of global total feed use (in metabolizable energy terms). The contribution of

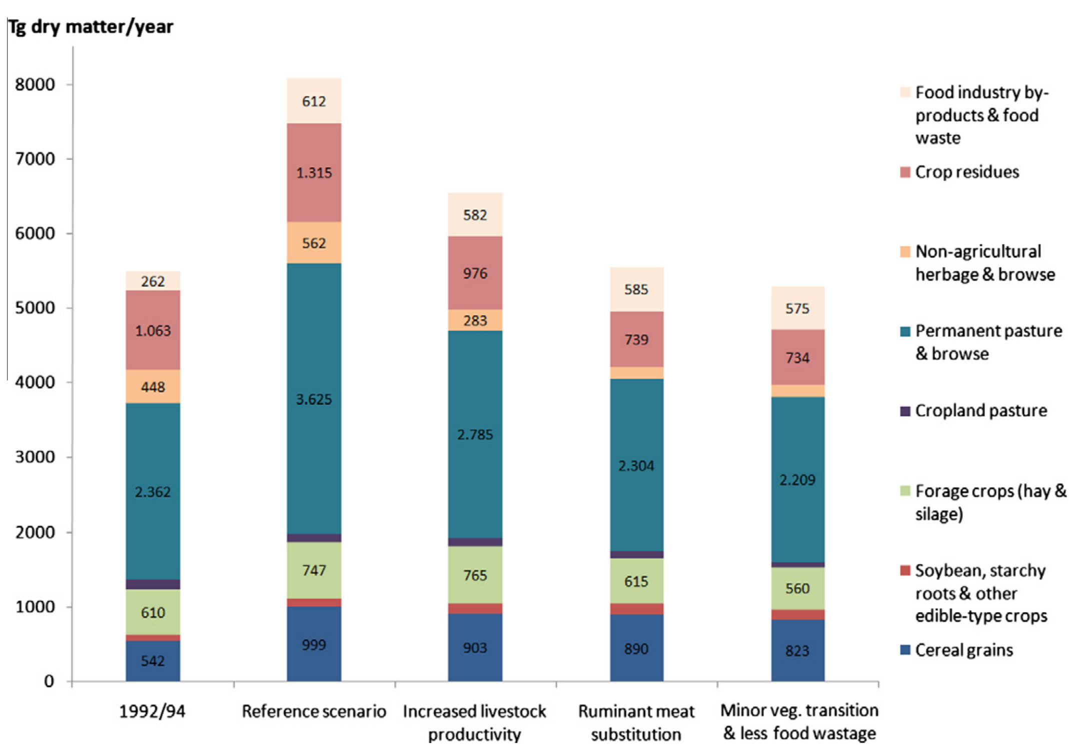

Fig. 6. Global feed use (amount eaten; sum for all livestock systems) in scenarios for 2030, specified by major feed categories. Note that soybean meal (and other oil meals) is included in the category 'Food industry by-products', while *whole* soybeans are included in the category 'Soybean, starchy roots and other edible-type crops'. The different components in the columns appear in the same order as in the legend. Data for 1992/1994 from Wirsenius (2000, 2003a,b).

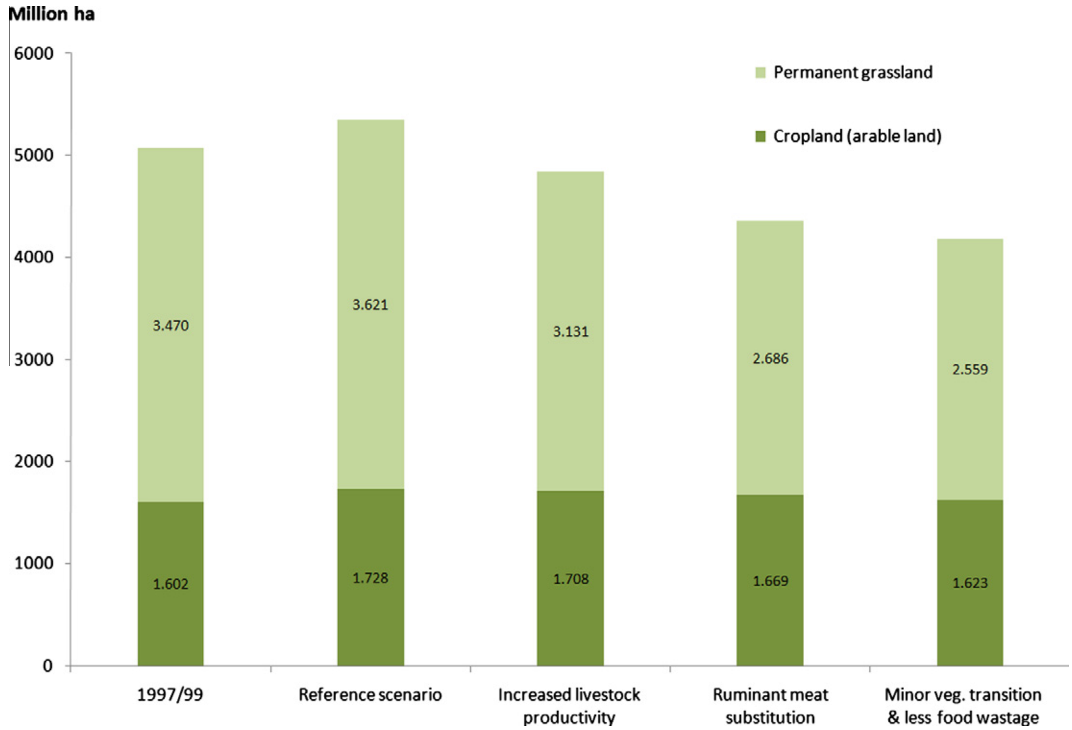

Fig. 7. Extent of global agricultural land in scenarios for 2030. Cropland area includes land used also for non-food crops (mainly cotton and rubber), which FAO projects to be roughly 50 Mha in 2030. It also includes land use for cultivation of food-type crops that are used for non-food purposes (e.g. transportation fuels, chemicals), a use which applies mainly to various oil crops, sugarcane, maize and potatoes. Specific projections on cropland area related to these non-food uses were not made by FAO, but a rough estimate suggest that it may correspond to about 100 Mha in the FAO projections for 2030. Data for 1997/1999 from Bruinsma (2003) and FAOSTAT.

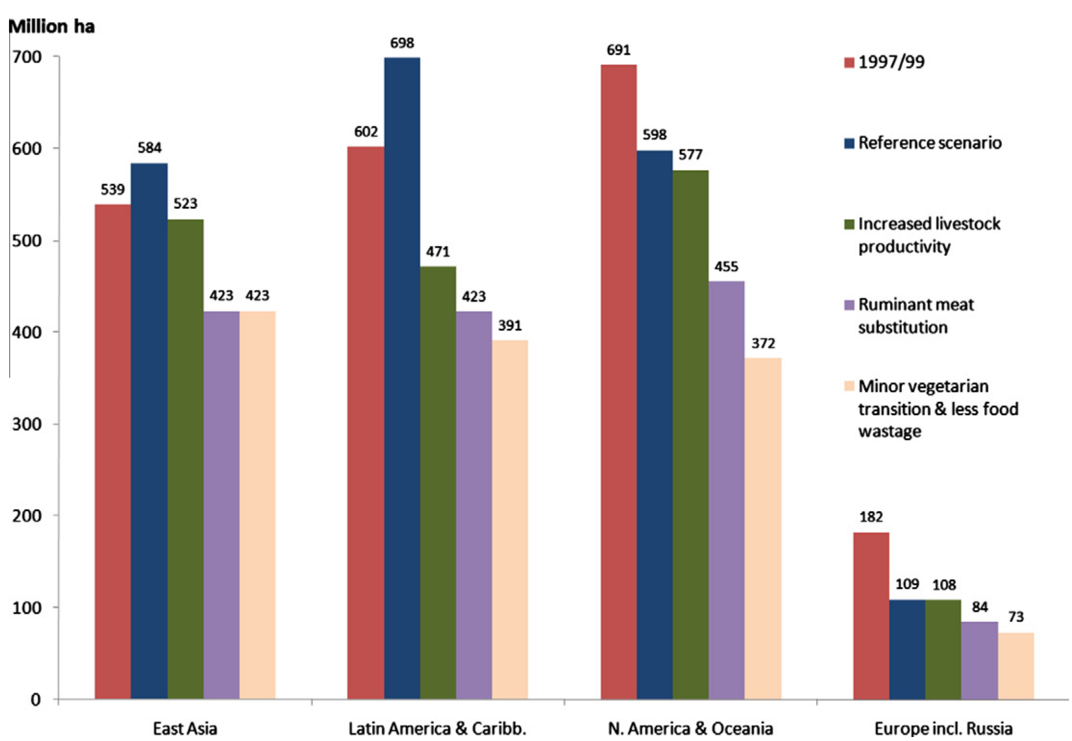

Fig. 8. Area of permanent pasture in scenarios for 2030 for a selection of regions. The different components in the columns appear in the same order as in the legend. Data for 1997/1999 from FAOSTAT.

by-products and residues to global feed use is substantial, of the same magnitude as that of cereals and other edible-type crops, both amounting to about 23% of total. The largest feed category is grazed herbage and browse from permanent pastures and various types of non-agricultural land, which in total amounts to about 44% of global feed use. Feed use by ruminants completely overshadows that of other livestock, accounting for about 85% of global feed use.

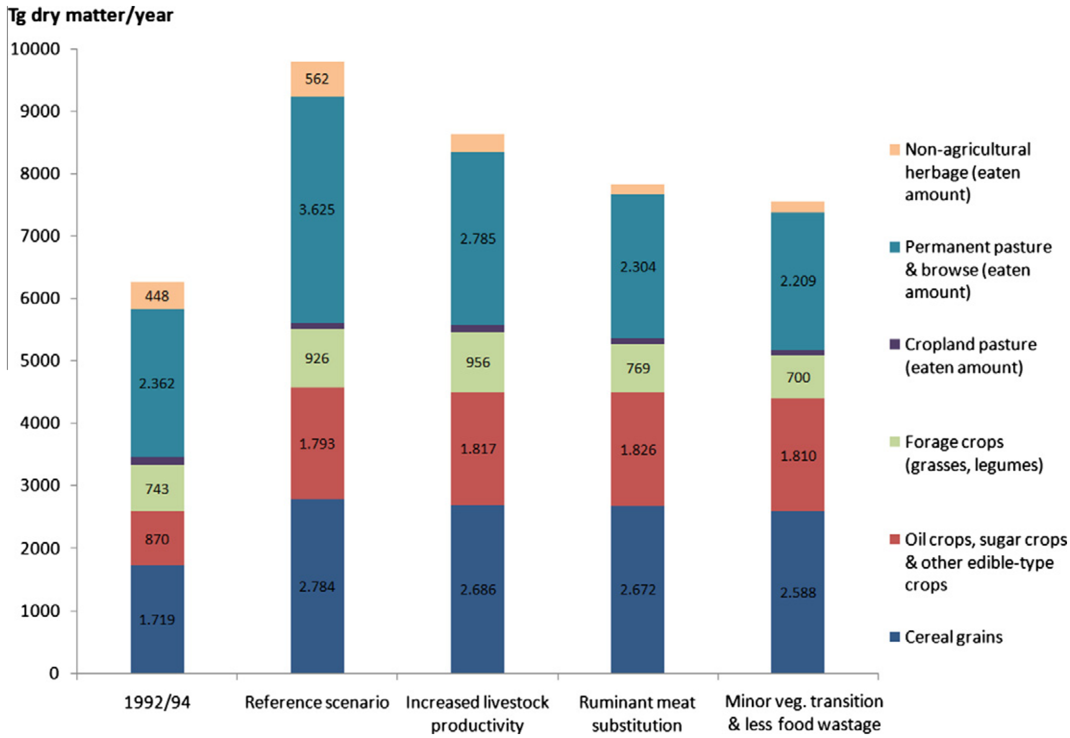

Fig. 9. Global harvested and grazed amount of crop (including crop residues), pasture and 'non-agricultural' (roadside, forest grazing) biomass in scenarios for 2030. Non-food crops (cotton, rubber, etc.) biomass are not included. The different components in the columns appear in the same order as in the legend. Data for 1992/1994 from Wirsenius (2000, 2003a,b).

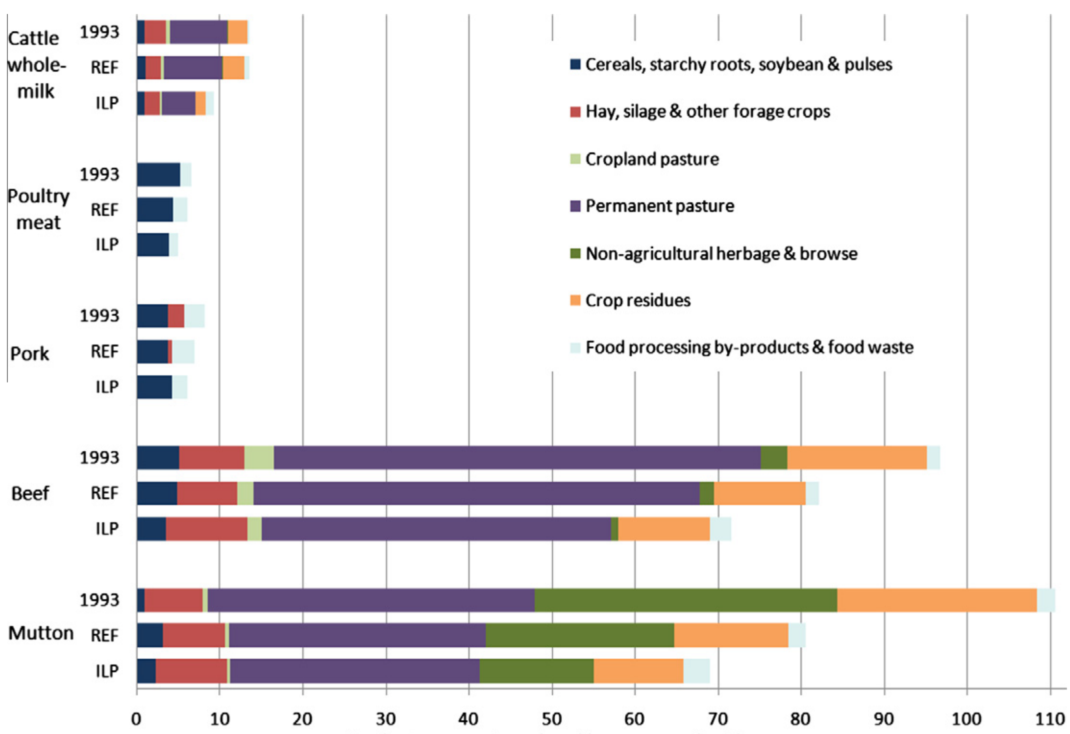

Fig. 10. Global averages of feed use per unit produced for major animal food systems in scenarios for 2030, specified by major feed categories. The graph shows feed use, as gross energy content of feed eaten, divided by gross energy content of product output. The different components in the bars appear in the same order as in the legend. Data for 1992/1994 from Wirsenius (2000, 2003a,b).

Agricultural land area in REF is about 280 Mha larger than today (Fig. 7), in relative terms an expansion by 5%. This is small in comparison to the increase in extraction (harvest and grazing) of biomass from agricultural land, which in total for all biomass types is about 50% globally (Fig. 9). Thus, most of the global increase in biomass extraction comes from raised yields and extraction per unit area, rather than expansion of the agricultural area.

Table 7
Overview of principal parameters determining global land requirements of animal food production in 1992/1994 and 2030. Note that in the reference scenario, data on animal food production and livestock numbers equal those of the FAO projections (Bruinsma, 2003), whereas data on feed intake, crop and pasture yield, and land area are estimates and results of this study. Data on animal food production and livestock numbers in 1992/1994 are from FAOSTAT; other data for 1992/1994 are based on Wirsenius (2000, 2003a,b).

Year and scenario	Animal food production (Tg fresh weight)				Livestock numbers (billions)				Feed intake (Tg dry weight)		Crop and pasture yield (Mg DM ha^{-1} $year^{-1}$)		Land area (billion ha)	
	Ruminant meat	Milk (whole milk)	Pork and poultry	Egg	Cattle and buffaloes	Sheep and goats	Pigs	Poultry	Ruminants	Pigs and poultry	Cropland biomass harvested[1] per ha	Perm. pasture intake per ha	Cropland	Permanent pasture
1992/1994	65.7	529	125	42	1.46	1.74	0.88	13.1	4 790	720	2.8	0.68	0.54	3.47
Reference scenario/FAO projection	109	866	266	84	1.87	2.34	1.06	24.0	6880	1230	3.6	1.0	0.61	3.6
Change fr. 1992/1994	66%	64%	113%	100%	28%	34%	21%	83%	44%	69%	29%	47%	13%	4.3%
Increased livestock productivity	As in the reference scenario				1.40	1.90	0.82	17.8	5 550	1 010	3.7	0.89	0.59	3.1
Change fr. 1992/1994					−4%	9%	−7%	36%	16%	40%	32%	31%	9%	−10%
Ruminant Meat Substitution	86.3	866	288	84	1.11	1.51	0.87	19.0	4 480	1 080	3.5	0.86	0.55	2.7
Change fr. 1992/1994	31%	64%	130%	100%	−24%	−13%	−1%	45%	−6%	49%	25%	26%	2%	−22%
Minor Vegetarian Transition and Less Food Wastage	79.8	850	267	84	1.06	1.47	0.82	18.2	4 290	1 020	3.5	0.86	0.51	2.6
Change fr. 1992/1994	21%	61%	114%	100%	−28%	−16%	−7%	39%	−10%	41%	25%	26%	−6%	−26%

These global figures are the sum of very divergent regional numbers. In Latin America and Sub-Saharan Africa, cropland area expands by 44 Mha (22%) and 71 Mha (30%) respectively, whereas it shrinks in East Europe by 36 Mha (17%) (Supplementary Table A1). Similarly, permanent pasture area increases in low and medium-income regions, especially in Latin America and Sub-Saharan Africa, by 100 Mha (16%) and 150 Mha (18%), respectively, whereas it decreases in industrialized regions – in the two European regions combined by as much as 70 Mha (40%) (Fig. 8).

4.2. Feed and land use in scenarios of increased livestock productivity, dietary changes, and less food wastage

In ILP, RMS and MVT, global feed use is considerably lower than in REF (Fig. 6). Global agricultural land area is smaller in all scenarios compared with both REF and today's use (Fig. 7). The lower area numbers are mainly due to substantial decreases in permanent pasture area compared to REF – for cropland, areas are greater than today in all scenarios.

In ILP, global animal food production is the same as in REF, i.e., 60–110% higher than today, depending on category (Table 7). However, since the increase in production in ILP is obtained by more productive animal systems, the number of animals remains at about current levels, except in the case of poultry. Despite keeping animal numbers at roughly current levels, feed use in ILP is significantly higher than present, since these more productive animals consume more feed per animal, mainly due to their average live weights, growth rates, and milk/egg yields being higher.

In comparison to REF, global feed use in ILP is about 20% lower. This corresponds to an increase in global average feed-to-food efficiency from 5.1% in REF to 6.2% in ILP (both in gross energy terms). Almost the entire drop in feed use comes from much less grazing on permanent pasture and non-agricultural land and of crop residues (Fig. 6). Global agricultural land area related to animal food production in ILP is about 510 Mha (13%) lower than in REF (Table 7); almost the entire difference can be attributed to a drop in permanent grassland area. As to the feed use of cereals, soybeans and other edible-type crops, it should be noted that direct comparisons between REF and ILP should be made with caution, since different approaches were used for estimating feed rations in those scenarios. As described in Section 3.4, in REF, regional feed use of cereals, etc., was set equal to the feed use in the projections in Bruinsma (2003), i.e., feed use of these feed types was exogenously determined. In contrast, in ILP (and RMS and MVT), feed rations were determined from exogenous constraints, such as nutrient density requirements, as described in Table 5, i.e., in these cases feed use of cereals, etc., was determined endogenously.

At the regional level, there are large differences in how feed and land use change from REF to ILP. In Latin America, which exhibits the largest relative changes, total feed use is about 32% lower (Supplementary Table A1), mainly due to much lower intake of permanent pasture (down 38%), which results in a substantial decrease in permanent grassland area (Fig. 8). In contrast, for cropland-produced feedstuffs, use in Latin America is much higher in ILP than in REF (up 40%), and this region is the only one showing a larger cropland area in ILP compared to REF (up 8%, see Supplementary Table A2).

The industrial regions demonstrate the opposite pattern. In the two European regions combined, permanent pasture intake and grassland area essentially remain the same as in REF (Fig. 8), and use of cropland-produced feedstuffs decreases by about 11%. The reason there is no decrease in permanent pasture despite higher livestock productivity, has to do with the links between the dairy and beef cattle systems. Given unchanged production of milk, an increase in dairy cow milk yield leads to a decrease in the number of dairy cows and therefore also the number of dairy calves that can be reared for meat production. Given unchanged demand for cattle meat, the lower supply of dairy cattle calves must be compensated by a higher supply of beef cattle meat, whose feed rations typically (mainly for economic reasons) has a higher share of permanent pasture, but also a significantly lower feed-to-food efficiency (for biological reasons, see Wirsenius, 2003b) than dairy calves meat. Therefore, to fully exploit the land savings of increased milk yields, cattle meat demand must decrease to the same extent as the decrease in dairy cattle meat supply.

In RMS, global feed use is 15% lower than in ILP and about 30% lower than in REF (Fig. 6). Owing to the larger share of more feed-efficient meat in RMS, global average feed-to-food efficiency increases to 7.3% from 6.2% in ILP. Compared to ILP, there are substantial decreases in intake of grazed feed on permanent pasture and non-agricultural land (down 20%), as well as of crop residues (down 24%). Interestingly, the use of cropland-produced feedstuffs is lower in RMS (down 9%), despite production of pork and poultry, whose production relies mainly on cereals and other cropland-produced feeds, at 8% higher than in ILP. This is due to the much lower feed-to-food efficiency of ruminant meat systems, which means that despite a relatively low share of cropland feedstuffs in the feed ration, they use on average globally more cropland-produced feedstuffs per unit of meat than do pork and poultry meat systems. For instance, as the results of this study show, beef cattle systems use, on average globally, roughly three times more cropland feedstuffs per unit of meat than do pig and poultry systems (Fig. 10). (For comparison, a similar difference, but somewhat lower – about two times more cropland for beef than pork, per unit of meat – was found in Stehfest et al. (2009). Global agricultural land area related to animal food production in RMS is about 480 Mha (13%) lower than in ILP, and 990 Mha (24%) lower than in REF (Table 7). The changes in land use are more or less proportional to those of feed use since average global crop yields and pasture intake per ha differ little between RMS and ILP.

In MVT, global agricultural area is about 170 Mha (4%) lower than in RMS (Fig. 7). This scenario concerned only regions with high per-capita meat consumption and/or high degree of food wastage, and had substantial impact on assumed food consumption patterns and food wastage only in the regions of North America and Oceania and West Europe. In these regions, total agricultural area is about 15% lower (105 and 18 Mha, respectively) than in RMS. In both regions, the decrease in cropland area due to lower meat consumption and food wastage is about 10 times greater than the increase in cropland area related to the higher consumption of vegetables, fruits and other vegetable food.

5. Discussion

5.1. General limitations of data and method used in scenarios

The model used in this study is purely bio-physical and does not include any economic parameters. Thus, the balance in the scenarios between different means to increase output, e.g. increased intensity in land use or livestock production versus expansion of area, was not based on explicit economic valuation. The same applies to the balance between different types of feed and livestock production systems, e.g. permanent pasture versus feed produced on cropland. The bio-physical nature of the model also means that feed ration formulation in this study was not as unambiguous and economically consistent as it might have been in the case of using an economic model with an economic optimization routine for determining feed rations.

Although the bio-physical parameter assumptions in the scenarios were based on implicit economical considerations, the use of economic modeling might have yielded rather different results. On the other hand, economic models, such as general or partial equilibrium models, are weak in assessing long-term developments, since they lack agronomic and technological detail and their parameter values are derived from past experience. These limitations are particularly severe in scenarios where future policy, economic, and agronomic conditions deviate substantially from those of the past, as well as in cases where new, not previously used, technology emerges.

Availability and quality of the data varied significantly between parameter groups. Among the parameters that had a decisive influence on principal scenario results, the most uncertain were the empirical bases for the productivity of permanent grasslands and feed energy value of permanent pastures, especially in low and medium-income regions. Improving the empirical bases of these parameters is paramount for enhancing the accuracy of the land use estimates in this study.

5.2. Food end-use and human diets in the RMS and MVT scenarios

The assumption in RMS of a partial shift from ruminant meat to pork and/or poultry is a change already taking place in high-income regions; ruminant meat consumption is slowly declining (Fig. 2), whereas poultry consumption is increasing rapidly. This trend of switching away from ruminant meat could be boosted by upcoming factors, including increasing prices of agricultural land and feedstuffs, and implementation of stricter environmental and climate policies. As ruminant meat requires more land and feed than pork and poultry, increases in land and feed prices might translate into higher price increases for ruminant meat than for pork and poultry. Ruminant meat, on average, also generates higher emissions of greenhouse gases and other pollutants per unit of meat, compared to pork and poultry. Therefore, implementation of stricter climate and environmental policy measures in the agricultural sector are likely to raise beef prices more than pork and poultry. Price elasticity data for the EU indicate that such changes in relative prices would lead to a substitution of mainly poultry, and to a lesser extent pork, for ruminant meat (Wirsenius et al., in press).

Long-run price increases of land and feed may result from increasing marginal supply costs within the food sector, driven by the increasing global food demand. But they may also stem from growing competition for agricultural land and crops from the emerging bioenergy sector, driven by implementation of climate policies and/or increasing fossil fuel prices. If climate policies are introduced that substantially raise the cost of emitting CO_2, the profitability of using agricultural land for bioenergy will increase. Analyses of the impact of higher CO_2 costs on agriculture suggest that it will lead to significant increases in land rents as well as farm gate prices of crops and animal products (Schneider and McCarl, 2003; Johansson and Azar, 2007). Other analyses of the impact of a greater agricultural bioenergy sector indicate that policy measures that specifically promote bioenergy (e.g. the EU biofuels directive, or the US ethanol subsidies) also lead to substantial increases in land and food prices (Hazell and Pachauri, 2006; Tokgoz et al., 2007; von Braun, 2007).

In contrast to RMS, the assumptions in MVT of a partial substitution of vegetable food for meat cannot be motivated by referring to recent trends. Total per-capita meat consumption in North America and Western Europe shows no signs of leveling off – over the past 10 years consumption has continued to increase by around 0.5% per year. Unless there is a shift in preferences, a higher share of vegetable food does not seem likely without changes in policies or technological development in food industry. With further development of the technology for producing plant protein isolates, inclusion of plant-derived proteins in minced meat could reach 25–35% (Smil, 2002). If applied to all minced meat consumed globally, this would imply a substitution of about 5–7% of total meat consumption with plant protein. For ruminant meat, however, the substitution rate would be much higher, since a much larger fraction of ruminant meat is consumed as minced meat – in the US more than 50%.

The assumptions in MVT of reduced food wastage at the retail and household levels also clearly go against current trends. In North America and Oceania and Western Europe, food wastage continues to rise steadily. Little research has been carried out on this topic, and there is poor understanding of the reasons behind the existence of large differences in food wastage between different high-income countries; wastage ranges from 25% to 40% of the food supplied at the wholesale level. Improved packaging and durability of food products could contribute significantly to decreased food wastage. For example, shelf-life of fruits and vegetables can be extended substantially by applying edible coatings (ENVIROPAK, 2004).

5.3. Feed use and permanent pasture productivity and area in REF scenario

The scenarios provide results on livestock feed use and the corresponding area of permanent pasture. There are very few studies available with comparable analyses of feed use and pasture areas. Bouwman et al. (2005) estimated global feed requirements in 2030 using the same data on crops and animal food production as Bruinsma (2003), i.e. the same data as in REF. Despite this, the estimate of global feed use in Bouwman et al. (2005) is almost 20% lower than in REF. Different structures in the model descriptions of both livestock systems and feed categories prevent full analysis of this difference. The representation of livestock systems was partly more disaggregated than in this study, with two types of beef and dairy cattle systems (pastoral and mixed/landless), but also more aggregated (sheep and goats were grouped to one single system, as were poultry and egg production). There was also a higher level of aggregation in the feed use description: five feed types were distinguished, in contrast to about 45 in this study. One reason for the difference in feed use is the much lower feed-to-meat numbers for sheep/goats, averaging globally 16 and 26 for mixed and pastoral systems in Bouwman et al., respectively, compared to 53 for sheep meat in this study (Table 4). This disparity alone explains about 0.7 Pg, or almost half of the difference in total feed use. The feed-to-meat numbers for sheep/goats in Bouwman et al. seem inexplicably low, since even in European high-productive sheep systems – whose productivity levels by far exceed global averages – typical feed-to-meat numbers are no lower than about 20 (SNV, 1997).

In REF, the permanent pasture area expands in the five low and medium-income regions (in total ~320 Mha, or 12%, see Supplementary Table A2), with particularly substantial expansions in the land-abundant Latin America and Sub-Saharan Africa. These area increases are directly linked to the predominantly large increases in ruminant numbers projected in Bruinsma (2003) in these regions: for cattle and buffaloes, 40–50% (except in S. Asia, 10%), and for sheep and goats, 30–45%. Obviously, such large increases in ruminant numbers are likely to require substantial increases in permanent pasture areas.

5.4. Livestock productivity, feed use, and permanent pasture productivity and area in ILP, RMS, MVT

In ILP (and in RMS and MVT) we assumed faster growth in livestock productivity until 2030 than did Bruinsma (2003). This hypothesis was coupled with the assumption of a faster transition toward higher land-use intensity of livestock production in low and medium-income regions, with higher pasture productivity and a larger use of cultivated feeds of good nutritive quality. In low and medium-income regions, the assumed livestock productivity levels are far from any biological limits. Therefore, of relevance here are to what extent the assumed growth rates – rather than the productivity levels as such – are attainable. Overall, our assumed annual growth rates in productivity are well below assessments of possible growth rates carried out by livestock specialists. For example, in their analyses of Chinese livestock systems, Simpson et al. (1994) concluded that the national average milk yield is likely to reach 6000 L year^{-1} in 2025, or 9000 L year^{-1} if assuming a more wide-spread application of advanced biotechnology, such as embryo-transfer. These milk yield levels correspond to annual growth rates of 3.7% and 4.9% from the base year 1990 in Simpson et al., which can be compared with the 3.3% annual growth of the milk yield in East Asia in our ILP scenario (Table 3). Current milk yield in China is about 3000 L year^{-1}, far above the FAO projections for 2030 of about 2000 L year^{-1}. Simpson et al. also assumed relatively high annual growth rates in beef meat productivity to 2025: in their base scenario 3.0%, and if assuming wider implementation of advanced biotechnology 3.9%. Both numbers are higher than any of the beef productivity growth rates assumed in ILP.

Increases in livestock productivity and the transition toward higher land-use intensity in livestock production are already underway in most developing countries, driven by current policy and economic and technological factors. These trends could be strengthened by a number of possible upcoming factors, in particular the growing bioenergy sector, but also stricter policies for limiting livestock's environmental and climate impact, as well as extended and enforced protection of remaining natural ecosystems.

As mentioned in Section 5.2, rising fossil fuel prices and introduction of climate policies would increase the demand for land for bioenergy, which could lead to significant increases in agricultural land rents and farm gate prices. Such increases in costs and prices would have effects on the structure of agricultural production, since the higher value of cropland and permanent pasture would make a more intense use of those lands more profitable. This would push ruminant production toward towards higher land-use intensity, with a larger reliance on cultivated feeds than on pasture and a higher feed-to-food efficiency. Hence, an emerging bioenergy sector would, overall, work as a driver for faster growth in livestock productivity and a faster transition toward higher land-use intensity in livestock production.

Steinfeld et al. (2006) concluded that a principle means of limiting livestock's environmental impact is to reduce its land requirements and the related use of water, nutrients and other resources. This overall strategy of reducing livestock's land requirements should be accompanied by a careful intensification of existing permanent pastures and cropland. Steinfeld et al. put forward a wide-ranging set of policy measures for limiting the environmental impact by livestock, including: (i) correcting distorted prices by removing subsidies and imposing taxes, also on land, (ii) strengthening land titles to increase incentives for augmenting long-term productivity and intensity of land use, (iii) strengthening institutions controlling forests, and other natural ecosystems, to counteract agricultural expansion. Obviously, were such stricter environmental policies implemented, they would work to reverse the current trend of agricultural land expansion, especially with respect to grazing land, and push livestock production toward higher land-use intensity.

6. Conclusions

This study concludes that if food and agriculture develop according to projections made by the FAO, global agricultural area

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is likely to expand substantially, by about 280 Mha by 2030. This would imply increased deforestation pressure, with further loss of biodiversity and increased CO_2 emissions. However, a different situation in 2030 is possible, or even likely, given the possible implementation of stringent climate and environmental policies and growing demand for land for food and bioenergy. This study concludes that there is substantial scope for land-minimizing growth of world food supply by efficiency improvements in the food-chain, particularly in animal food production, and dietary changes toward less land-demanding food.

More specifically, our main findings are:

- Assuming faster, yet achievable, growth in animal food productivity than the FAO assumes, global agricultural land use could decrease by about 230 Mha from current levels, by 2030 – or about 500 Mha lower than in the reference scenario, i.e. the area implied in the FAO projections.
- If this higher productivity is combined with an assumed 20% substitution of pig and/or poultry for ruminant meat in human diets, agricultural area could decrease by an additional 480 Mha, resulting in a total of about 1000 Mha less than in the reference scenario.
- Assuming a minor transition towards vegetarian food (25% decrease in meat consumption per-capita) in high-income regions, combined with a somewhat lower food wastage rate (15–20% decrease) at retail and household levels, agricultural land use in these regions decreases by about 15%, compared to the Ruminant Meat Substitution scenario.

Other notable findings include:

- Substituting pork or poultry for beef saves permanent pasture land, but in most cases significant cropland, too. This is mainly due to the inherently much lower biological productivity and feed-to-food efficiency of ruminant meat systems compared to pork and poultry systems.
- Increasing the milk yield of dairy cows does not in itself lead to significant land savings as long as beef demand remains unchanged, since the lower production of dairy beef that follows from higher milk yields has to be compensated by a higher production of more land-demanding beef cattle meat. To fully exploit the land savings of increased milk yields, therefore, beef demand must decrease to the same extent as the decrease in dairy cattle beef supply.
- Crop residues and food industry by-products, in particular, are likely to play an increasingly important and land-saving role in the global feed supply, and could account for some 20% of global feed use in 2030, which is about the same as the expected use of cereals as feed. Oil meals and other protein-rich by-products are likely to account for the greater share, 75–85%, of the demand for protein concentrate feed in 2030.

Faster growth in livestock productivity and dietary changes favoring less land-demanding food consumption could develop through technology and management improvements, the implementation of stricter climate and environmental policies, and changes in food preferences. They may also be induced by increased competition for agricultural land due to rising food demand and a growing bioenergy sector. The higher prices of land and feed resulting from this competition are likely to stimulate faster growth in livestock productivity and a faster transition away from low-intensive grazing towards mixed farming systems and improved pastures with higher yields. Higher land and feed prices will also moderate the consumption of animal food, particularly ruminant meat.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agsy.2010.07.005.

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