Climatic Change (2009) 95:83–102
DOI 10.1007/s10584-008-9534-6

Climate benefits of changing diet

**Elke Stehfest · Lex Bouwman · Detlef P. van Vuuren ·
Michel G. J. den Elzen · Bas Eickhout · Pavel Kabat**

Received: 11 April 2008 / Accepted: 24 October 2008 / Published online: 4 February 2009

Abstract Climate change mitigation policies tend to focus on the energy sector, while the livestock sector receives surprisingly little attention, despite the fact that it accounts for 18% of the greenhouse gas emissions and for 80% of total anthropogenic land use. From a dietary perspective, new insights in the adverse health effects of beef and pork have lead to a revision of meat consumption recommendations. Here, we explored the potential impact of dietary changes on achieving ambitious climate stabilization levels. By using an integrated assessment model, we found a global food transition to less meat, or even a complete switch to plant-based protein food to have a dramatic effect on land use. Up to 2,700 Mha of pasture and 100 Mha of cropland could be abandoned, resulting in a large carbon uptake from regrowing vegetation. Additionally, methane and nitrous oxide emission would be reduced substantially. A global transition to a low meat-diet as recommended for health reasons would reduce the mitigation costs to achieve a 450 ppm CO_2-eq. stabilisation target by about 50% in 2050 compared to the reference case. Dietary changes could therefore not only create substantial benefits for human health and global land use, but can also play an important role in future climate change mitigation policies.

1 Introduction

About 18% of the global greenhouse gas emissions are caused by livestock production, with the main contributors being methane (CH_4) from enteric fermentation, nitrous oxide (N_2O) from manure and fertilizer, and carbon dioxide (CO_2) from

---

E. Stehfest (✉) · L. Bouwman · D. P. van Vuuren · M. G. J. den Elzen · B. Eickhout
Netherlands Environmental Assessment Agency, Global Sustainability and Climate,
P.O. Box 303, 3720 AH Bilthoven, The Netherlands
e-mail: Elke.Stehfest@pbl.nl

L. Bouwman · P. Kabat
Earth System Science and Climate Change Group, Wageningen University Research
Centre (WUR), P.O. Box 47, 6700 AA Wageningen, The Netherlands

land-use change and agricultural energy use (Steinfeld et al. 2006). Ruminants (cattle, sheep and goats) account for a large share of total livestock emissions, because they are less efficient in converting forage into useful products than monogastrics (pigs and poultry). Grazing land for ruminants covers more than 25% of the global land surface, and about 70% of global agricultural land. Due to the vast areas needed, grazing systems have a high impact on the carbon cycle and therefore the climate through deforestation and land degradation (Asner et al. 2004). Furthermore, ruminants constitute the largest anthropogenic source of CH_4, released by enteric fermentation (Crutzen et al. 1986). Finally, all animal production systems require feed crops, currently covering 34% of global cropland (Steinfeld et al. 2006).

IPCC recently concluded that under scenarios without climate policy increasing greenhouse gas concentrations may cause global mean temperature to rise by up to 7°C compared to pre-industrial levels by the end of this century (IPCC 2007b). Greenhouse gas emissions would need to be reduced substantially to avoid such an increase in global mean temperature. For instance, to limit temperature increase to less than 2°C compared to pre-industrial levels (the long-term climate target adopted by the European Union) with a chance of approximately 50% (based on probability distribution functions for climate sensitivity), greenhouse gas concentrations have to be stabilized below 450 ppm CO_2-eq. (2.6 W m^{-2}) (Meinshausen et al. 2006; IPCC 2007b). In order to achieve this, greenhouse gas emissions in the year 2050 need to be 40–80% lower than in 2000 (Fisher et al. 2007).

A combination of technical measures in the energy system, abatement technology for non-CO_2 gases and reforestation (Fisher et al. 2007; IPCC 2007a; van Vuuren et al. 2007) has been suggested as a means of achieving such rigorous mitigation targets. Recently, a few studies have pointed out that due to the importance of livestock as regards greenhouse gas emissions, dietary changes may lead to emission reductions (Aiking et al. 2006; McMichael et al. 2007). However, the effects of dietary changes in the context of mitigation scenarios and associated costs have yet to be studied quantitatively.

Dietary changes may not only be attractive from a climate perspective, the impacts they might have on human health and life expectancy are also of great interest from a public health perspective. While initially the public health sector has mainly focused on the consequences of obesity, there has recently been a rise in concern about the adverse effects of meat and other animal products. The consumption of beef and pork increases the risk of intestinal cancer (WCRF and AICR 2007), and there is some evidence that reducing the consumption of fatty meat may lower the risk of coronary heart disease (Li et al. 2005; Ding 2006) which has led to the revision of dietary recommendations from public health institutions (Willett 2001).

Here, we analyze how changes in the human diet may impact the technical and economic feasibility of ambitious climate stabilization targets. Using the integrated assessment model IMAGE 2.4 (MNP 2006), we compare four alternative dietary variants in terms of their greenhouse gas emissions and the corresponding costs for achieving stabilization of greenhouse gas concentrations at 450 ppm CO_2-eq. to a reference and mitigation scenario without these dietary changes (Section 2, Methods). The results for the reference case and the mitigation effort under an ambitions climate policy without dietary change are presented first (Section 3.1 and 3.2). Subsequently, the four variants of dietary transitions are analyzed with respect to their land use and related climate effects (Section 3.3). Based on that, mitigation scenarios are developed for all variants to study the effect of dietary transition on climate mitigation and costs (Section 3.4). Major uncertainties of our study are addressed in a sensitivity analysis (Sections 2.5 and 3.5) and, we conclude with a discussion of our results and their implications Section 4.

2 Methodology

2.1 The IMAGE modeling framework

The Integrated Model to Assess the Global Environment (IMAGE version 2.4) is an integrated assessment model framework that explores the long term dynamics of global change as a function of drivers such as demographic and economic development and developments in the energy and agricultural system (MNP 2006). Within IMAGE, energy scenarios are developed using the energy model TIMER (van Vuuren et al. 2006). The climate policy model FAIR (den Elzen et al. 2007) is used to calculate global emission pathways that lead to a stabilization of the atmospheric greenhouse gas concentration. The developments in the energy system and in agricultural demand and production are described on the scale of world regions (26 regions for energy, 24 for agriculture). Environmental parameters are simulated at a 0.5 by 0.5° resolution by the ecosystem, crop and land-use models of IMAGE. Greenhouse gas emissions from energy and industry, land use, land-use change, crop and livestock production systems and natural ecosystems are mainly computed on the basis of guidelines of the Intergovernmental Panel on Climate Change (IPCC 2006). IMAGE also describes the biosphere–atmosphere exchange of carbon dioxide (CO_2), and feedbacks of climate and atmospheric CO_2. Global mean temperature change is first calculated by the simple Atmosphere–Ocean model MAGICC (Wigley and Raper 1992; Hulme et al. 2000), and subsequently downscaled via a pattern-scaling method (Schlesinger et al. 2000) to project climate change at the 0.5 by 0.5° resolution.

Here we briefly discuss the components, approaches and assumptions of the IMAGE model relevant to the dietary transitions and the consequences for land use, greenhouse gas emissions and the carbon cycle.

2.1.1 Energy system

The energy system (TIMER) describes the long-term dynamics of the production and consumption of nine primary energy carriers for five end-use sectors in 26 world regions (van Vuuren et al. 2006). In the model, long-term prices are determined by resource depletion and technology development. These prices, combined with fuel preferences, are used in a multinomial logit model to select a combination of technologies. Emissions of the energy system are obtained by multiplying energy consumption and production flows with emission factors. A carbon tax can be used to induce a dynamic response such as increased use of low or zero-carbon technologies, energy efficiency increase and end-of-pipe emission reduction technologies. The carbon tax required to achieve a certain climate policy target is calculated by the FAIR model, taking into account baseline emissions and cost curves for CO_2 and non-CO_2 emission reductions (see Section 2.4).

2.1.2 Land use change

The agricultural model of IMAGE distinguishes seven crop groups and five animal categories. Crop and pasture productivity is calculated according to the Agro-Ecological Zone (AEZ) approach (Leemans and van der Born 1994). As a starting point for the simulations, IMAGE 2.4 uses a land cover map based on satellite data and statistical information for the distribution of agricultural land (Klein Goldewijk et al. 2007). For the historical period 1970–2000 agricultural land cover is calibrated with data from the FAO (2007). Starting from this base-map, scenarios of agricultural demand, trade and production are either obtained from an agricultural economy model linked to IMAGE (Eickhout et al. 2008), or—like in this study—prescribed from other sources. The land area needed to meet the regional production depends not only on the domestic demand itself, but also on changes in crop and grass productivity. If the regional increase in productivity is slower than the increase in production, agricultural area will expand at the cost of natural vegetation, resulting in emissions of CO_2 and N_2O caused by this conversion, and other emissions associated with biomass burning. If productivity increase is faster than production increase, agricultural land is abandoned and the regrowing vegetation starts to sequester carbon. The regional production of agricultural goods is distributed spatially on the basis of a set of allocation rules (Alcamo et al. 1998). These rules include crop productivity and socioeconomic considerations such as distance to existing agricultural land, water and roads. Bioenergy crops are assumed to be produced on abandoned agricultural land and natural grasslands only and therefore do not cause deforestation.

2.1.3 Land use for livestock production systems

IMAGE describes two aggregated livestock production systems, namely pastoral systems and mixed/landless systems. Pastoral systems covering about two-thirds of the global area of permanent pasture are dominated by ruminant grazing. Part of the pastoral land has a very low productivity (less than 20% of the global maximum productivity) and is referred to as extensive pasture. In many countries this land is actually in (semi)desert areas and other land with unfavourable soil or climate conditions. Landless ruminant production systems are included in mixed/landless systems since they have the same interrelationships with crop and grass production systems (feed crops, fodder, manure, etc.) as livestock production in mixed systems. By taking different feed efficiencies into account, the model calculates the total feed requirement and its composition for both systems (Bouwman et al. 2005). Pork, poultry meat and eggs are assumed to be produced in mixed and landless systems. In the reference scenario, there is a gradual increase of the proportion of the total ruminant meat and milk production in mixed and landless systems, which have a larger contribution of feed crops to the animal rations than pastoral systems.

2.1.4 Non-CO_2 emissions from agricultural and livestock production systems

Methane emissions from enteric fermentation are calculated in IMAGE from the total feed requirements and feed composition (Bouwman et al. 2005), and methane conversion rates (IPCC 2006). Methane emissions from animal waste are based on estimates of Steinfeld et al. (2006). Nitrous oxide emissions from animal manure management systems are largely based on IPCC data (IPCC 2006). While emission factors for N fertilizer use, manure spreading and grazing are assumed not to change over time in the absence of climate policy, future emissions per unit of product will change due to efficiency improvements in crop and animal productivity. Mitigation policies (Section 2.4) can also reduce the emissions factors directly.

2.1.5 Carbon cycle

In IMAGE, the carbon exchange between terrestrial ecosystems and the atmosphere is, like all other land-related processes in IMAGE calculated at a 0.5 by 0.5° resolution. Each grid cell is characterized by its climate (temperature, precipitation and cloudiness), soil and land cover (natural ecosystems or agriculture). The distribution of 14 natural land-cover types is computed with a modified version of the BIOME model (Prentice et al. 1992) on the basis of climate, soil and atmospheric CO_2 concentration. If natural vegetation re-grows after abandonment of pasture or cropland, the net primary production increases to its maximum value over a biome-specific transition period, ranging from 2 years for grasslands to 20 years for boreal forest. Reaching the equilibrium biomass, however, takes much longer (van Minnen et al. 2000). The terrestrial C cycle modeling in IMAGE as affected by changes in land cover and climate is described in detail elsewhere (Klein Goldewijk et al. 1994; van Minnen et al. 2000).

2.2 Reference scenario

We use a so-called reference scenario as a point of reference for the assessment of the mitigation policies and the dietary variants. This reference scenario portrays a possible future with default assumptions on meat consumption (i.e. an income-driven increase in per capita meat consumption, see below), and no climate policy, and was designed as a 'business-as-usual' (or 'median') development path (Table 1). The assumptions for the implementation of this scenario into the IMAGE system have been based on two main sources. For the socio-economic projections and the energy sector, we used the IMAGE implementation of the reference scenario of the OECD Environmental Outlook (Organization of Economic Co-operation and Development) (OECD 2008). In terms of energy use, this scenario loosely follows the projections of the International Energy Agency (IEA 2006).

For agricultural production, the IMAGE model was calibrated to follow the projections of the Food and Agriculture Organization of the United Nations (FAO) for 2000–2050 (Bruinsma 2003; FAO 2006). The FAO was regarded the most authoritative source, although alternative projections of meat consumption and production exist (e.g. Fiala 2008). Characteristics of food consumption and the agricultural system in 2000 and 2050 are provided in Table 2 for OECD countries, the group

Table 1 Global population, GDP per capita and anthropogenic greenhouse gas emissions for 2000, 2030 and 2050 in the reference scenario

	Population	GDP	Energy	Industry	Land use
	Million inhabitants	US$ per capita	GtC-eq per year		
2000	6,093	5,584	7.6	0.5	3.0
2030	8,236	10,282	12.9	0.8	3.3
2050	9,122	16,012	15.1	1.0	3.3

Table 2 Characteristics of the agricultural system in the reference case

	2000	2000	2000	2050	2050	2050
	OECD	BRIC	Other	OECD	BRIC	Other
Consumption of animal products[a] [kg/cap/year]						
Beef, sheep and goat meat	24	8	9	30	15	16
Milk	126	48	43	141	90	54
Pork	31	16	4	37	25	6
Poultry and eggs	38	16	13	47	27	21
Crop consumption[a] [kg/cap/year]						
Grains[b]	119	176	153	114	172	151
Other crops[c]	38	29	37	41	37	48
Grain yield increase 2000–2050[b] [%]				40	71	42
Grass yield increase 2000–2050[b] [%]				47	54	31

Per capita crop and meat consumption change in crop yields and grazing intensity for the three world regions OECD, BRIC (Brazil, Russia, India, China) and all other countries

[a] Total consumption in FAO definition, i.e. not including losses along the processing chain, reported for products at market water content. Milk also includes indirect use via dairy products

[b] Covering the categories temperate cereals, maize, rice, and tropical cereals, in dry matter

[c] Covering the categories roots and tuber, pulses, and oil crops, in dry matter

of Brazil, Russia, India and China (BRIC), and the Rest of the World. More detail on all model parameters, inputs and outputs can be obtained from the authors.

2.3 Scenarios of dietary change

In order to explore the impact of dietary transitions, four variants of the reference scenario were developed with partial or complete substitution of meat by plant proteins. These four variants are (a) complete substitution of meat from ruminants (NoRM), (b) complete substitution of all meat (NoM), (c) complete substitution of all animal products (meat, dairy products and eggs) (NoAP) and finally (d) partial substitution of meat based on a healthy diet variant (*HealthyDiet*, HDiet). The stylized variants of complete substitutions should be regarded as analytical constructs allowing for a detailed assessment of the effects of specific food products on land use, carbon cycle, greenhouse gas emissions, and mitigation options.

The fourth variant concerns the implementation of reduced meat consumption, which was based on the dietary recommendations by the Harvard Medical School for Public Health and is considered to be healthy by the author (Willett 2001) (Table 3). The main characteristic of the *HealthyDiet* variant is the recommended sparing consumption of ruminant meat and pork, while consumption of fish, poultry and eggs is advised with zero to two servings per day. With a serving size of 70 g, assuming that sparing consumption means one serving of beef and pork per week, and not allowing global total fish consumption to increase, we arrive at an average daily per capita intake of 10 g beef, 10 g pork, and 46.6 g of chicken meat and eggs (Table 4). These daily amounts of beef, pork and poultry/eggs are approximately 52%, 35% and 44%, respectively, of the global average consumption in 2050 in the reference case. The diet was implemented globally in our model, with no regional differentiation, which leads to higher meat intake than in the reference case in some areas of the world. Since some developing countries might not be able to increase

Table 3 Description of the reference scenario and the four dietary variants

Variant	Description
Reference	Agricultural production for 2000–2030 (Bruinsma 2003) and 2030–2050 (FAO 2006). The 2000–2030 projections are country-scale and aggregated to the 24 world regions of the IMAGE model. The projections for 2030–2050 have a continental scale
No Ruminant Meat (NoRM)	As reference, but with complete substitution of proteins from ruminant meat (cattle, buffaloes, sheep and goats) by plant-proteins, starting in 2010 and completed by 2030. By-products such as wool and leather are also assumed to be substituted by other materials
No Meat (NoM)	As NoRM, with additional substitution of white meat (pork, poultry) by plant proteins, starting in 2010 and completed by 2030
No Animal Products (NoAP)	As NoM, with additional substitution of milk and eggs by plant proteins, starting in 2010 and completed by 2030
Healthy Diet (HDiet)	"Healthy Eating" recommendations from the Harvard Medical School (Willett 2001) implemented globally for meat and eggs, starting in 2010 and completed by 2030. See also Table 4

their meat consumption, this global implementation is a conservative assumption and might therefore underestimate the impact of this diet shift.

In our study, the transition to these alternative diets was assumed to take place between 2010 and 2030, and no implementation or other costs are taken into account. We assumed that meat, egg and milk proteins (including milk and all dairy products such as butter and cheese) are substituted by proteins from pulses and soybeans[1] in all variants. The substitution is done solely on the basis of protein content, which is assumed to be 20% for meat, 20% for pulses and 4% for milk on the basis of fresh weight. Soybeans are assumed to make up 60% of the additional production of food-pulses, which is the current (year 2000) fraction. Consumption of all other food crops (except for the additional pulses and soybeans for substitution) as well as the characteristics of the livestock production system like feed composition and conversion efficiencies are assumed to be the same as in the reference case (e.g. Table 2, last two lines. For more information on the reference case please contact the authors).

The energy used for the processing and transport of livestock products exceeds that for plant-based products, and contributes about 1% to total energy use (Steinfeld et al. 2006). To account for the decrease in energy use due to the substitution of animal products, the energy consumption per product group was calculated for all scenarios and implemented in the energy model, reducing global energy consumption by 0.3–0.9% in the dietary variants.

---

[1] Pulses (beans, peas, lentils and chickpeas) are the seeds of legumes used as food crops. The term 'pulses', as employed by the FAO, is reserved for crops harvested solely for the dry grain. For this reason it excludes green beans and green peas, which are considered vegetable crops, as well as legume crops grown for oil extraction (oilseeds like soybeans and peanuts), and crops used exclusively for sowing (clovers and alfalfa). In our study, however, the additional soybeans are harvested mainly for their grains and therefore fall under the definition 'pulses'

Table 4 Meat intake and consumption in the *HealthyDiet* variant

Aggregated group	Intake [g/pers/day]	Total consumption at retail[a] [g/pers/day]	Total consumption[b] [g/capita/day]
Ruminant meat	10.0	11.6	17.1
Pork	10.0	11.6	15.5
Poultry and eggs	46.5	57.3	69.3
Fish	23.5[c]		

[a] Including losses at the household/food service level of 15% or 28% and 1% or 2% at the retail level for meat and eggs, respectively (Kantor et al. 1997)

[b] Total consumption in FAO category ("dressed carcass") calculated on the basis of the meat fraction in dressed carcass (Forrest et al. 1995)

[c] Calculated from 1997 total fish consumption (European Communities 2006) and 2050 population, assuming no increase in total global fish consumption. Fish consumption is not simulated in IMAGE

2.4 Mitigation strategies and costs

For the mitigation scenarios we used a global emission pathway that complies with a 450 ppm CO_2 eq. stabilization target (or a radiative forcing of 2.6 W m^{-2}) (den Elzen and van Vuuren 2007). The emission pathway allows overshoot at a level of 510 ppm CO_2 eq. (3.2 W m^{-2}) in the middle of 21st century. For the climate policy cases, we used the FAIR (den Elzen et al. 2007) model to distribute the emission reductions required to achieve this global emission pathway across sectors, gases and world regions in a cost-optimal way. In order to do so, the FAIR model uses marginal abatement costs curves. The marginal abatement costs curve for CO_2 emissions in the energy sector are derived from the TIMER model by imposing different levels of emission permit prices. This results in an increasing market share for fuels with low carbon emissions (such as solar and wind power) at the cost of high-emission options (coal, oil), and a price driven increase in energy-efficiency. Marginal abatement cost curves for non-CO_2 gases (including agriculture) are based on the EMF-21 project (Weyant et al. 2006) and on the extensions proposed by Lucas et al. (2006). The marginal abatement curves within the FAIR model are also used to calculate the global annual abatement costs, expressed in 1995 US$ (i.e. corrected for inflation) and international permit price.

It should be noted that the exponential shape of the abatement cost curves implies that mitigation costs are not related linearly with the required emission reductions, but exponentially, because the cheapest mitigation solutions are implemented first. Accordingly, when the distance to the mitigation target is decreasing, most expensive options are avoided first, and mitigation costs decrease exponentially.

On the basis of the annual abatement costs, the discounted cumulated abatement costs are calculated cover 2005–2050 time period (for more details, see den Elzen and van Vuuren 2007).We apply the discounting method of Weitzman (2001) which uses an initial rate of 4% in 2000, decreasing over time to 2% in 2050. We express the discounted cumulated abatement costs as a fraction of the cumulated, discounted GDP.

2.5 Sensitivity analysis

In order to test the robustness of our results under variations in a number of important model assumptions and parameters a sensitivity analysis has been performed.

The terrestrial carbon cycle and especially the carbon uptake of abandoned cropland and pasture play a crucial role in this study. We therefore studied the sensitivity of our results to different assumptions on CO_2 fertilization re-growth of vegetation and abandonment of agricultural land. For CO_2 fertilization, the increase in net primary production (NPP) by a doubling of CO_2 concentration was reduced from 35% to 17.5%. The pace at which natural vegetation recovers on abandoned agricultural land is another important uncertainty. As described above, the time needed for reaching maximum net primary production ranges from 2 years for grasslands to 20 years for boreal forest (van Minnen et al. 2000). In a sensitivity run, this recovery time was increased by a factor of 2. A further important uncertainty is the effect that drastic demand changes may have on the agricultural system. In the variants, we had assumed that crop yields are identical to those in the reference case. However, a decreasing demand and a subsequent decrease in land prices is likely to slow down the improvement of agricultural technology and crop yields. And even more directly, the abandonment of vast areas of pasture and cropland for feed production may lead to extensification of the remaining agriculture. Therefore, we included a sensitivity run with a slower productivity increase than in the reference case and the variants. We adjusted intensification so that only half of the abandonment of cropland and intensive pasture would occur at the global scale.

In general, all possible sensitivity runs can be classified into three groups. (a) Sensitivities that impact both the reference case and dietary variants in a similar way (CO_2 fertilization), (b) sensitivities that have a stronger impact on the low-meat variants than on the reference case (recovery time of natural vegetation), and (c) sensitivities that only affect the dietary variants (agricultural system feedbacks). These sensitivity runs were performed for the reference case and one dietary variant, the *HealthyDiet* variant, and analyzed for variations in the modeled CO_2 concentrations and mitigation cost. Thereby, the analysis of mitigation costs under the changed CO_2 emission and concentration pathways illustrates the relationship between the distance to the mitigation target, and the associated costs.

Beyond these uncertainties in the biosphere and the agro-economic system, the choice of the discount rate often has a very strong and determining effect on the results of climate policy scenarios and mitigation costs (Weyant 2000). We therefore applied alternative discounting methods based on UK Treasury (2003), Nordhaus (2007) and Stern (2006), and a constant 5% discount rate which is also used in IPCC's third and fourth assessment reports.

3 Results

3.1 Reference scenario

Under the reference scenario, global population increases from 6 to 9 billion people between 2000 and 2050, and global average GDP per capita almost triples from 5.5 to 16 thousand US$ (Table 1). As a result, greenhouse gas emissions rise from 11.2 GtC-eq in 2000 to 19.7 GtC-eq in 2050 (78% increase) (where GtC-eq means gigatonne of CO_2 carbon equivalent), with energy-related emissions remaining dominant (Table 1). This development is in line with mean values of the total range of emission scenarios (without climate policy) presented in Fisher et al. (2007).

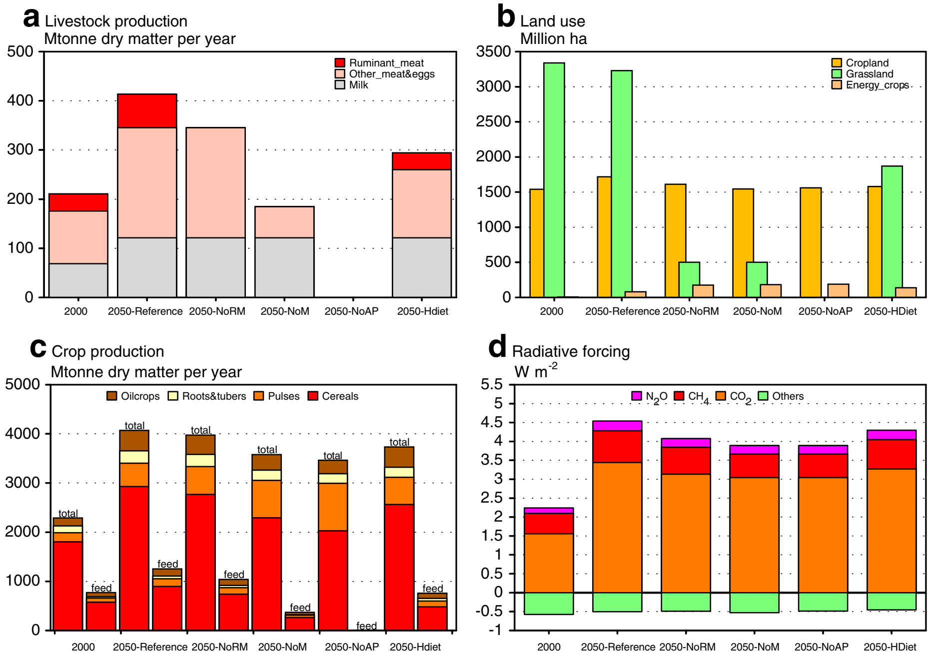

Fig. 1 Main characteristics of the reference scenario and the four variants with reduced consumption of ruminant meat (*NoRM*), meat (*NoM*) animal products (*NoAP*), and a supposedly healthy diet (*HDiet*) for the categories: livestock production (**a**), land use (**b**), crop production (**c**) and radiative forcing (**d**)

In the same period, livestock production doubles (Fig. 1), mainly driven by population growth and increasing per capita meat consumption. However, increasing productivity in both crop and livestock production, and a gradual shift in consumption from ruminant meat to pork and poultry meat results in an agricultural land expansion of only 11% (Fig. 1). The total annual land-use related greenhouse gas emissions increase by 10% from 3 GtC-eq. to 3.3 GtC-eq. between 2000 and 2030 and remain constant thereafter (Tables 1 and 5). Within this total, the annual non-CO_2 greenhouse gas emissions from land use increase from 2 GtC-eq in 2000 to 2.6 GtC-eq. in 2030 and 2.8 GtC-eq. in 2050. Over time, methane emissions increase only slowly as consumption growth is somewhat counterbalanced by an increase in efficiency. While methane emissions are reduced from 0.5 to 0.4 g CH_4 per kg meat

Table 5 Land-use emissions in 2000 and 2050 for the reference scenario and four dietary variants

	GtC eq.
2000	3.0
2050-Reference	3.3
2050-NoRM	1.7
2050-NoM	1.5
2050-NoAP	1.1
2050-HDiet	2.1

and milk (expressed as dry matter), total global methane emissions from enteric fermentation and animal waste increase steadily throughout the scenario period from about 100 Tg CH_4 per year in 2000 to close to 170 Tg per year in 2050. It should also be noted that increasing (industrial) monogastric production will not only cause additional greenhouse gas emissions from manure, but also induces an increasing demand for feed crops, resulting in considerable greenhouse gas emissions associated with their production and fertilizer input.

3.2 Mitigation effort without considering dietary change

On the basis of the reference scenario, we developed a scenario that stabilizes greenhouse gas concentrations at 450 ppm CO_2-eq in the long term. Meeting this target requires an emission pathway with reductions of 67% in 2050 compared to the reference scenario (Fig. 2a). Most mitigation takes place in the energy sector, with energy efficiency improvement, carbon capture and storage, and increased use of renewable energy resources being the most important options. Bioenergy crops play an important role, although their production is confined to abandoned agriculture land and natural grasslands. In 2050, the total contribution of modern bio-energy

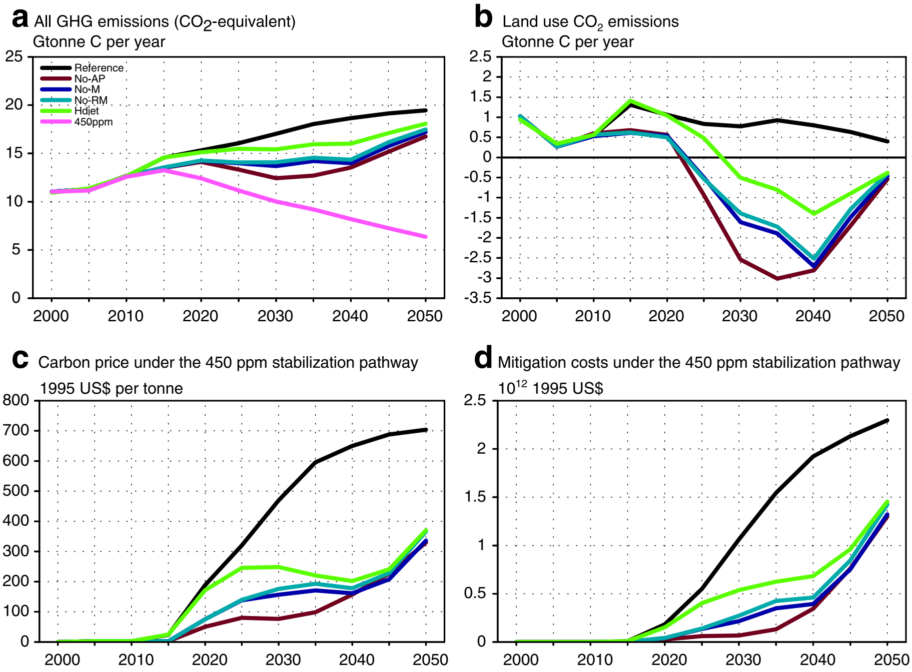

Fig. 2 Total greenhouse gas emission pathways (**a**), land-use related CO_2 emissions (**b**), carbon price (**c**) and mitigation costs (**d**). **a** and **b**, show the results of no-climate policy cases for the reference scenario, and the four variants with reduced consumption of ruminant meat (*NoRM*), meat (*NoM*) animal products (*NoAP*), and a supposedly healthy diet (*HDiet*) as well as the emission trajectory under the 450 ppm stabilization profile (**a**). **c** and **d** show the cost associated with achieving this profile from the reference cases and all variants

is 130 EJ—of which 55 EJ from residues. The carbon price increases to 650 US$ per tonne C-eq in 2050 to induce the required emission reductions (Fig. 2c). Overall direct mitigation costs for the period 2005–2050 amount to about 1% of GDP based on cumulated net present values (Table 6), which is in good agreement with other cost estimates for low stabilization targets (Fisher et al. 2007).

3.3 Scenarios of dietary change

The first three stylized alternative variants have important consequences for global land use. The strongest impacts occurs for pasture area, which is reduced by 80% or 2,700 Mha (in NoRM and NoM) and by 100% or 3,200 Mha (in NoAP) compared to the reference scenario. In all three variants there is a reduction of the global cropland area. The reductions amount to 6% in the NoRM variant (Fig. 1), as the arable area required for crops to feed ruminants exceeds the area for producing plant proteins. A further decrease (4%) in global crop area occurs when all meat is substituted by plant proteins in the NoM variant (Fig. 1). The additional substitution of milk and eggs by plant proteins in NoAP leads to complete abandonment of pasture and a small increase in the global cropland area.

Substitution of animal proteins with plant proteins involves a reduction in the use of feed crops (see also Bouwman et al. 2005), and an increase in food crops. Due to the large differences in land requirement of the different products, the net effect on total land use is not intuitively evident. The following example, assuming "global mean" production characteristics, illustrates the resulting land use requirements (Table 7). The production of 100 kg of beef protein (500 kg beef) requires 0.6 ha of cropland (assuming 30% feed crops in the ration, a conversion rate of 20 kg feed per kg of beef, and an average crop yield of 5,000 kg per hectare). For producing the same amount of protein from pulses (with a crop yield of 2,000 kg per hectare) a cropland area of only 0.25 ha is needed. The production of 100 kg of milk protein (2,500 kg milk) using 30% concentrate in the ration, at a conversion rate of 1 kg feed per kg of milk, requires 0.1 ha of cropland. The production of 100 kg of protein from pork (500 kg meat), with 60% concentrates in the ration at a conversion rate of 6 kg feed per kg of pork, requires 0.36 ha of cropland. Hence, the substitution of milk by

Table 6 Abatement costs as a fraction of GDP, calculated by dividing the discounted cumulated abatement costs (2005–2050) by the discounted cumulated GDP (2005–2050)

Discounting method	Abatement costs as fraction of GDP (2005–2050)				
	Reference	NoRM	NoM	NoAP	HDiet
Weitzman (2001), default	1.04	0.31	0.27	0.20	0.48
Constant discounting (5% per year)	0.80	0.23	0.20	0.14	0.38
UK Green Book (UK Treasury 2003)	0.96	0.29	0.25	0.18	0.45
Nordhaus (2007)	1.14	0.35	0.31	0.23	0.52
Stern (2006)	1.28	0.40	0.35	0.27	0.58
Ranges of abatement costs relative to the reference [%]	100	29–31	25–38	17–22	45–48

Results are shown for the reference scenario and the four dietary variants under the default discount rate, and under the different discounting methods of the sensitivity analysis

Last row shows the ranges of cumulative abatement costs (NPV of costs as NPV of GDP (2005–2050) relative to the reference [percent]

Table 7 Example of differences in cropland requirement for producing 100 kg of protein from ruminant meat, milk, pork and pulses

Type of product	Protein [kg]	Product (meat/ milk) [kg]	Feed conversion [kg feed per kg product]	Crops in feed ration [fraction]	Crop production [kg]	Crop yield [kg ha^{-1}]	Area [ha per 100 kg] protein]
Ruminant meat	100	500	20	0.3	3,000	5,000	0.6
Milk	100	2,500	1	0.2	500	5,000	0.1
Pork	100	500	6	0.6	1,800	5,000	0.36
Pulses	100	NA	NA	NA	500	2,000	0.25

NA not applicable

plant proteins in this example causes an increase in cropland area, while less cropland is needed when beef or pork are replaced. Thus, in this example the areas required for producing feed crops for milk and meat rise with the increasing proportion of concentrate in feed rations (intensive production systems) and decreasing efficiency of feed conversion.

The agricultural area that becomes redundant through the dietary transitions can be used for other agricultural purposes such as energy crop production, or will revert to natural vegetation thus acting as a carbon sink. In particular, in our model runs it is the re-establishment of temperate, boreal and warm mixed forest (17% of global pasture area) as well as tropical savannah, scrubland, woodland and forest (35%) that results in more biomass than under managed grazing land (Table 8). Pastures with low productivity reverting to tundra and (semi-) deserts (~20%) or steppe (30% of the global pasture area) do not constitute an important CO_2 sink, given the small carbon stocks in these systems. In total, the global greenhouse gas emissions (CO_2 and non-CO_2) from agricultural production systems, calculated for the three stylized variants, show considerable reductions in relation to the reference scenario (Table 5). For the most extreme variant (NoAP), the cumulative emission reduction in the 2010–2050 period amounts to 17% for CO_2, 24% for CH_4 and 21% for N_2O (Fig. 1). The largest reduction of greenhouse gas emissions by product category is caused by the substitution of ruminant meat (Fig. 2a), with a large terrestrial

Table 8 Potential natural vegetation types as a percentage of the global pasture area in 2000 [percent]. Pasture area here includes extensive and intensive pastures

Tundra	2
Wooded tundra	1
Boreal forest	2
Grassland/steppe	27
Cool coniferous forest	1
Temperate mixed forest	3
Temperate deciduous forest	4
Warm mixed forest	7
Hot desert	18
Scrubland	13
Tropical woodland	5
Savanna	15
Tropical forest	3

net CO_2 sink of about 30 GtC over the whole period compared to a net source of 34 GtC in the reference case (Fig. 2b). The stepwise additional abolishment of other meat types, and other animal products, does not induce such a high additional greenhouse gas emissions reduction. Methane emission due to enteric fermentation and from animal waste as well as the N_2O emissions associated with animal waste are reduced significantly (in NoRM and NoM), or even dropping to zero (in NoAP). The contribution of the additional carbon sink and avoided deforestation contributes 65–75% to the total cumulative emission reduction. It should be noted, however, that contrary to reductions in N_2O and CH_4 emissions, the CO_2 uptake is a transient phenomenon (Fig. 2a and b). The stylized dietary variants show a reduction of greenhouse gas concentrations of 57 to 76 ppm CO_2-eq., and a reduction of radiative forcing of about 0.5 W m^{-2} compared to the reference scenario in 2050 (Fig. 1d).

As expected, the *HealthyDiet* variant has smaller, but still significant effects compared to more extreme variants discussed so-far. Although total consumption of animal products is substantial (Fig. 1a), the reduction in ruminant meat has a large impact. Crop and pasture area is reduced by 135 and 1360 Mha, respectively, compared to the reference case (Fig. 1b). Greenhouse gas emissions in the *HealthyDiet* variant are about 10% lower than in the reference case, whereby the initially large difference is getting smaller again when the additional carbon uptake by regrowing vegetation starts to level off (Fig. 2a). As discussed above, the reduction in nitrous oxide and methane emissions is permanent, while the increased uptake of CO_2 is a transient phenomenon. In total, the reduced emissions and increased uptake in the *HealthyDiet* variant result in greenhouse gas concentration being reduced by 30 ppm CO_2-eq. in 2050, compared to the reference case.

3.4 Mitigation efforts based on the dietary change scenarios

As for the reference case, we also developed mitigation scenarios on the basis of the dietary variants. Due to the reduced greenhouse gas emissions and concentrations, the remaining emission reductions required to meet the emission profile of the 450 ppm CO_2-eq scenario (Fig. 2) are 31–47% lower in the dietary variants compared to the reference case. Therefore, less emission reduction is needed in the energy sector. As a result, the carbon price required to induce changes shows a slower increase over time (Fig. 2c), as less emission reduction is required to achieve the stabilization targets (Fig. 2a). Consequently, the mitigation costs are much lower than under the reference case (Fig. 2d). The overall net present value of mitigation costs over the 2000–2050 period in both NoRM and NoM are reduced by 70% compared to the reference case (0.3% of GDP and not 1%) and by even more than 80% in the NoAP case (Table 6). As the CO_2 uptake by regrowing vegetation in the dietary variants is a temporary process, the differences in costs between the reference case and the dietary variants are most significant in the short term and are subsequently decreasing over time.

The reduction in emissions in the *HealthyDiet* variant also leads to a lower carbon price needed to meet the emission pathway (Fig. 2c). Therefore, direct mitigation costs under the *HealthyDiet* variant are reduced by 54% compared to the reference case (i.e. 0.48% of GDP, all referring to net present values). Compared to the most ambitious emission reduction discussed during the last UNFCCC Conference of Parties meeting in Bali (50% reduction in 2050 compared to 2000), the *HealthyDiet* variant would already contribute an estimated 20% to the cumulative emission reductions over the 2010–2050 period.

For all variants, reduction of mitigation costs relative to the reference case is much larger than the reduction of emissions relative to the reference case. In the *HealthyDiet* variant, for example, cumulative emissions are reduced by about 20%, while costs are reduced by more than 50% (both cumulated over the period 2010–2050). This is caused by the exponential shape of the abatement cost curves, which make the costs increase or decrease exponentially with the distance to the mitigation target (see Section 2.4).

Due to the abandonment of crop and pasture land, more land is available for bio-energy crops. In our analysis, we assume that 75% of the abandoned agricultural land and 50% of natural grasslands are potentially available to grow woody bio-energy crops, maize or sugar. The total potential for bioenergy from woody biomass in 2050 increases from 170 EJ in the reference case to around 450 EJ in the *HealthyDiet* variant. However, due to the much lower mitigation requirement, the resulting lower carbon price in the dietary variants and the heterogeneous cost structure for bioenergy, only a fraction of this additional potential is actually used. The net result is that the bio-energy use in 2050 in the *HealthyDiet* variant is 170 EJ, i.e. 40 EJ more than in the reference case. Consistent with the lower carbon price, the average price of woody bio-energy crops that are actually used is also lower, by nearly 35%. The contribution of the larger bioenergy potential to the reduction of mitigation costs under the dietary variants is small. Reduced emissions of CO_2, CH_4 and N_2O, and the additional terrestrial sink, play a much bigger role.

3.5 Sensitivity analysis

The sensitivity simulations for CO_2 fertilization, recovery of natural vegetation and the agricultural system (see Section 2.5) result in different outcomes for land use and CO_2 concentrations, under the absence of climate policy (Table 9). Therefore

Table 9 Results from the sensitivity analysis for CO_2 fertilization, recovery period of natural vegetation and agricultural system feedbacks, for CO_2 concentration in 2050, and abatement costs to meet the 450 ppm stabilization pathway

	CO_2-eq. conc. [ppm] in 2050		Discounted cumulated abatement costs as a fraction of discounted cumulated GDP (2005–2050)		Abatement costs relative to the reference case [%]
	Reference	HDiet	Reference 450 ppm	HDiet 450 ppm	HDiet/ Reference 450 ppm
Standard settings	666	636	1.04	0.48	46
Reduced CO_2 fertilization	678	649	1.33	0.63	47
Slower recovery period natural vegetation	671	645	1.18	0.65	55
Reduced agricultural intensification	666[a]	645	1.04[a]	0.63	60

[a] This sensitivity does not affect the reference case

the mitigation efforts and costs to achieve the 450 ppm mitigation pathway are also changed (Table 9). The reduction of CO_2 fertilization by a factor of two results in an approximately 12 ppm higher CO_2 concentration in 2050 compared to the standard settings in both the reference case and the *HealthyDiet* variant (Table 9). Therefore, mitigation effort is higher, and abatement costs as a fraction of GDP increase by about 30%. The relative difference, however, between the reference and the *HealthyDiet* variant does not change, and relative reduction in cumulative abatement costs compared to the reference is roughly 50%, similar to the standard settings. A slower recovery period of net primary productivity (NPP) for natural vegetation after the abandonment of pasture or cropland has a larger effect on CO_2 concentrations in *HealthyDiet* than in the reference case (9 and 5 ppm, respectively). Therefore abatement costs to meet the 450 ppm concentration target increase more significantly in *HealthyDiet*, and the relative abatement costs are only reduced to 55% of those in the reference case. For the sensitivity run with slower agricultural intensification (only half of the abandonment of crop and intensive pasture compared to the standard scenario) the CO_2 concentration in the *HealthyDiet* variant is 11 ppm higher than with the standard settings. As a result, the effort to meet the 450 ppm mitigation pathway is higher, and the relative abatement costs compared to the reference case increase from 47% in the standard settings to 60%. We can therefore conclude that even under these changed assumptions dietary changes have a substantial impact on mitigation costs, and that our results are robust under the studied sensitivity simulations.

Another uncertainty related to the re-growth of natural vegetation is the fate of extensive pastures after abandonment in some of the dietary variants. These extensive pastures which are often traditional nomadic systems (Suttie et al. 2005) may not be converted to potential natural vegetation for either cultural reasons or because re-establishment of other vegetation is not possible due to land degradation caused by long-term overgrazing. Not allowing abandonment of extensive pasture however had hardly any impact on the total carbon uptake and global CO_2 concentrations (results not shown) and was therefore not included in the sensitivity analysis. Most extensive pastures occur in areas where no carbon uptake will take place after abandonment and regrowth to natural vegetation. About 50% of global extensive pasture occurs in desert areas or regions with shrubland, and 37% is in areas with natural grassland (mainly steppe). The remaining area will (in the IMAGE model) revert to tundra (7%) or temperate forest (6%).

Alternative assumptions for discount rates have also been tested in a sensitivity analysis. The results show that there is a substantial effect on the absolute value of mitigation costs, but the relative difference between the variants is hardly influenced by these assumptions (Table 6).

4 Discussion

Our model experiment shows that changes in dietary patterns can be an effective means to decrease greenhouse gas emissions, in addition to more conventional strategies such as changes in the energy system, reforestation and the reduction of non-CO_2 gases by add-on abatement technology. While the stylized variants presented here are useful in illustrating the effects of dietary transitions, the *HealtyDiet* variant shows that an arguably more realistic scenario will also have significant effects on both climate change and mitigation costs. In addition to reductions in CH_4 and N_2O, the shift to low-meat diets induces a reduction in agricultural area, and subsequently leads to land availability for other purposes such as energy crops or nature reserves. The regrowth of vegetation on these abandoned areas leads to a substantial, though transient, uptake of CO_2.

There are numerous sources of uncertainty in the various components of IMAGE 2.4. For the results of this study, the assumptions with respect to the carbon cycle and the abandonment of agricultural land are of special importance. We have therefore tested variations of CO_2 fertilization, the recovery period of natural vegetation, and the potential feedbacks of decreasing demand on intensification in the agricultural system in a sensitivity analysis. By changes in the latter two factors, the economic benefits of the *HealthyDiet* scenario are reduced from about 50% to 40%. The impact of CO_2 fertilization, however, is smaller, as this changes the CO_2 concentration and mitigation costs for the reference case and the *HealthyDiet* variant equally. Different discounting methods also did not change the relative reduction in mitigation costs off all variants compared to the baseline. We can therefore conclude that our results are robust with respect to these uncertainties.

Further uncertainties that have been addressed in earlier work include a thorough evaluation of the carbon cycle model implemented in the IMAGE framework (Klein Goldewijk et al. 1994), proving that it is well in line with the literature (van Minnen 2008). Sensitivity analysis showed the reaction of the biosphere to increasing concentrations of CO_2 to be a dominant factor on both the global and regional scales, which conforms to other modeling studies (Sitch et al. 2005). In the context of this study, another uncertainty with respect to the carbon cycle is related to the potential natural vegetation on abandoned pastures, as it determines the carbon uptake when natural vegetation is regrowing after abandonment. The distribution of potential natural vegetation in the IMAGE model is calculated by a modified version of the BIOME model. In the context of this study, it was not possible to carry out a sensitivity analysis on the BIOME parameters, but earlier studies have shown that the pattern of natural vegetation calculated by the BIOME model agree reasonably well with observed vegetation patterns (Prentice et al. 1992).

Another important source of uncertainty is related to the potential contribution and cost of abatement options. The abatement costs of the IMAGE model compare well to other estimates (Fisher et al. 2007). A sensitivity analysis was performed to identify alternative assumptions which have a significant impact on overall abatement costs (van Vuuren et al. 2007). Most individual mitigation options did not affect the total abatement costs by more than 10% (up or downwards) until 2050, with the exception of energy crops, where the high end of the literature estimates on the supply potential, and introducing the option to capture and store CO_2 from bioenergy, would reduce costs by up to 40%. The compounded effect of taking all the options collectively, however, results in 40% lower to almost 100% higher costs in 2050. While this uncertainty in cost estimates has a significant effect on absolute cost estimates, the relative differences in costs between the different scenarios as used in this study will be much less affected by uncertainty in costs than the absolute numbers.

In this scenario study we have ignored possible socio-economic implications such as the effect of health changes on GDP and population numbers. We have not analyzed the agro-economic consequences of the dietary changes and its implications; such consequences might not only involve transition costs, but also impacts on land prices. The costs that are associated with this transition might obviously offset some of the gains discussed here. An interesting question is what kind of potential strategies could lead to lower consumption of meat, eggs and milk. While some authors have recently suggested reducing meat consumption via a special tax, others stress that no large changes can be expected through price mechanisms (Smil 2002). As assumed in the *HealthyDiet* variant, health concerns such as overnourishment in high-income countries and specific impacts of pork or beef may be important additional incentives for reducing the consumption of meat (Moreira and Padrao 2004). Consumption of animal products including ruminant meat in developing countries is increasing rapidly at the moment. Possibly, these trends can still be influenced towards meat preferences which are beneficial to both health and climate, before they turn into hard-to-change traditions. Impacts on livestock farmers (who will face income losses) might be an important barrier in implementing low-meat diets. Nevertheless, the benefits of dietary change to both health and climate mitigation and the feasibility of low stabilization targets as shown here are important enough to put this issue on the political agenda.

References

Aiking H, de Boer J, Vereijken J (eds) (2006) Sustainable protein production and consumption: pigs or peas? Springer, Dordrecht

Alcamo J, Kreileman E, Krol M, Leemans R, Bollen J, van Minnen JG, Schaeffer M, Toet S, de Vries B (1998) Global modelling of environmental change: an overview of IMAGE 2.1. In: Alcamo J, Leemans R, Kreileman E (eds) Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. Elsevier, Oxford, pp 3–94

Asner GP, Elmore AJ, Olander LP, Martin RE, Harris AT (2004) Grazing systems, ecosystem response, and global change. Annu Rev Environ Res 29:261–299

Bouwman AF, van der Hoek KW, Eickhout B, Soenario I (2005) Exploring changes in world ruminant production systems. Agric Syst 84:121–153. doi:110.1016 j.agsy 2004.1005.1006

Bruinsma JE (2003) World agriculture: towards 2015/2030. An FAO perspective. Earthscan, London

Crutzen PJ, Aselmann I, Seiler W (1986) Methane production by domestic animals, wild ruminants, other herbivorous fauna and humans. Tellus 38B:271–284

den Elzen MGJ, van Vuuren DP (2007) Peaking profiles for achieving long-term temperature targets with more likelihood at lower costs. Proc Natl Acad Sci U S A 104:17931–17936

den Elzen MGJ, Meinshausen M, van Vuuren DP (2007) Multi-gas emission envelopes to meet greenhouse gas concentration targets: costs versus certainty of limiting temperature increase. Glob Environ Change 17:260–280

Ding E (2006) Optimal diets for the prevention of stroke. Semin Neurol 26:11–23

Eickhout B, van Meijl H, Tabeau A, Stehfest E (2008) The impact of environmental and climate constraints on global food supply. In: Hertel TW, Rose S, Tol RSJ (eds) GTAP Working Paper No. 47 Chapter 9 of the forthcoming book economic analysis of land use in global climate change policy

European Communities (2006) Facts & figures on the CFP: basic data on the common fisheries policy. Office for Official Publications of the European Communities

FAO (2006) World agriculture: towards 2030/2050. Prospects for food, nutrition, agriculture and major commodity groups, Food and Agriculture Organization of the United Nations, Global Perspective Studies Unit, Rome

FAO (2007) FAOSTAT database collections (www.apps.fao.org), Food and Agriculture Organization of the United Nations, Rome

Fiala N (2008) Meeting the demand: an estimation of potential future greenhouse gas emissions from meat production. Ecol Econ 67(4):519–525

Fisher B, Nakicenovic N, Alfsen K, Corfee Morlot J, de la Chesnaye F, Hourcade J-C, Jiang K, Kainuma M, La Rovere E, Matysek A, Rana A, Riahi K, Richels R, Rose S, van Vuuren DP, Warren R, Ambrosi P, Birol F, Bouille D, Clapp C, Eickhout B, Hanaoka T, Mastrandrea MD, Matsuoko Y, O'Neill B, Pitcher H, Rao S, Toth F (2007) Issues related to mitigation in the long-term context. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds) Climate change 2007. Mitigation of climate change. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York, pp 169–250

Forrest JC, Aberle ED, Hedrick BB, Judge MD, Markel RA (1995) Principle of meat science. Freeman, San Francisco

Hulme M, Wigley T, Barrow E, Raper S, Centella A, Smith S, Chipanski A (2000) Using a climate scenario generator for vulnerability and adaptation assessments: MAGICC and SCENGEN version 2.4 workbook. Climate Research Unit, Norwich, UK

IEA (2006) World energy outlook 2006. International Energy Agency, Paris

IPCC (2006) IPCC guidelines for national greenhouse gas inventories, IPCC NGGIP programme, IPCC-TSU/IGES. Published by the Institute for Global Environmental Strategies (IGES), Hayama, Japan on behalf of the IPCC, Hayama, Japan

IPCC (2007a) Climate change 2007. Mitigation of climate change. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds) Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York

IPCC (2007b) Climate change 2007. The physical science basis. In: Solomon S, Chin D, Manning M, Marquis M, Averyt K, Tignor MMB, Le Roy Miller H Jr, Chen Z (eds) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York

Kantor LS, Lipton K, Manchester A, Oliveira V (1997) Estimating and addressing America's food losses. Food Review 20(1):2–12

Klein Goldewijk K, van Minnen JG, Kreileman GJJ, Vloedbeld M, Leemans R (1994) Simulation of the carbon flux between the terrestrial environment and the atmosphere. Water Air Soil Pollut 76:199–230

Klein Goldewijk K, van Drecht G, Bouwman AF (2007) Mapping contemporary global cropland and rangeland on a 5' resolution grid. J Land Use Sci 2:167–190

Leemans R, van der Born GJ (1994) Determining the potential global distribution of natural vegetation, crops and agricultural productivity. Water Air Soil Pollut 76:133–161

Li D, Siriamornpun S, Wahlqvist ML, Mann NJ, Sinclair AJ (2005) Lean meat and heart health. Asia Pac J Clin Nutr 14:113–119

Lucas P, van Vuuren DP, Olivier JGJ, den Elzen MGJ (2006) Long-term reduction potential of non-CO_2 greenhouse gases. Environ Sci Policy 10:85–103

McMichael AJ, Powles JW, Butler CD, Uauy R (2007) Food, livestock production, energy, climate change, and health. Lancet 370:1253–263. doi:10.1016/S0140-6736(07)61256-2

Meinshausen M, Wigley TM, van Vuuren DP, den Elzen MGJ, Swart R (2006) Multi-gas emissions pathways to meet climate targets. Clim Change 75:151–194

MNP (2006) Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), The Netherlands

Moreira PA, Padrao PD (2004) Educational and economic determinants of food intake in Postuguese adults: a cross-sectional survey. BMC Public Health 4:NIL 1–NIL 11

Nordhaus WD (2007) The challenge of global warming: economic models and environmental policy. Yale University, New Haven

OECD (2008) OECD environmental outlook to 2030, 2008. OECD, Paris

Prentice IC, Cramer W, Harrison S, Leemans R, Monserud RA, Solomon AM (1992) A global biome model based on plant physiology and dominance, soil properties and climate. J Biogeogr 19:117–134

Schlesinger ME, Malyshev S, Rozanov EV, Yang F, Andronova NG, de Vries B, Grübler A, Jiang K, Masui T, Morita T, Nakicenovic N, Penner J, Pepper W, Sankovski A, Zhang Y (2000) Geographical distributions of temperature change for scenarios of greenhouse gas and sulphur dioxide emissions. Technol Forecast Soc Change 65:167–193

Sitch S, Brovkin V, Von Bloh W, van Vuuren DP, Eickhout B, Ganopolski A (2005) Impacts of future land cover changes on atmospheric CO2 and climate. Glob Biogeochem Cycles 19: GB2013

Smil V (2002) Eating meat: evolution, patterns, and consequences. Popul Dev Rev 28:599–639

Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, de Haan C (2006) Livestock's long shadow. Environmental issues and options. Food and Agriculture Organization of the United Nations, Rome

Stern N (2006) The economics of climate change, the Stern review. Cambridge University Press, Cambridge, UK

Suttie JM, Reynolds SG, Batello C (2005) Grasslands of the world. Report No. Plant Production and Protection Series 34. Food and Agriculture Organization of the United Nations, Rome

UK Treasury (2003) The Green Book: appraisal and evaluation in central government. TSO, London

van Minnen JG (2008) The terrestrial carbon cycle on the regional and global scale. Modeling, uncertainties and policy relevance, PhD thesis. Wageningen University Research Centre (WUR), Wageningen

van Minnen JG, Leemans R, Ihle F (2000) Assessing consequences of dynamic changes in global vegetation patterns, using the IMAGE 2.1 model. Glob Chang Biol 6:595–611

van Vuuren DP, van Ruijven B, Hoogwijk MM, Isaac M, de Vries HJM (2006) TIMER 2: model description and application. In: Bouwman AF, Kram T, Klein Goldewijk K (eds) Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), publication number 500110002/2006, Bilthoven

van Vuuren DP, den Elzen M, Lucas P, Eickhout B, Strengers B, van Ruijven B, Wonink S, van Houdt R (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim Change 81:119–159. doi:10.1007/s10584-006-9172-9

WCRF, AICR (2007) Food, nutrition, physical activity and the prevention of cancer, a global perspective. World Cancer Research Fund/American Institute for Cancer Research, Washington D.C. AICR

Weitzman M (2001) Gamma discounting. Am Econ Rev 91:261–271

Weyant JP (2000) An introduction to the economics of climate change policy. Pew Center on Global Climate Change, Arlington, VA

Weyant J, Delachesnaye P, Blanford G (2006) An overview of EMF-21: multigas mitigation and climate change. Energy J Special Issue 3:1–32

Wigley TML, Raper SCB (1992) Implications for climate and sea level of revised IPCC emissions scenarios. Nature 357:293–300

Willett WC (2001) Eat, drink, and be healthy: the Harvard Medical School guide to healthy eating. Simon & Schuster, New York