Master Thesis

BIOENERGY AND OTHER DRIVERS OF LAND EXPANSION AND GREENHOUSE GAS EMISSIONS - A KAYA-LIKE DECOMPOSITION

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Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Arbeit selbstständig und eigenhändig sowie ausschließlich unter Verwendung der aufgeführten Quellen und Hilfsmittel angefertigt habe.

Berlin, den 03. Juli 2013 Ina Neher

Abstract

Currently, 12% of ice-free land is used as cropland. Agricultural production and land use change are responsible for 32% of total anthropogenic greenhouse gas (GHG) emissions in CO_2 equivalent. Population growth, changing diets and technological improvements are seen as the main drivers for past variations in cropland and GHG emissions. In the future, the demand for bioenergy is expected to add additional pressure on the agricultural sector. However, the individual contribution of the main drivers on cropland expansion and increasing GHG emissions remained undetermined.

This study aims to quantify the past and future influence of the main drivers on cropland expansion and rising GHG emissions. For this purpose, a Kaya-like decomposition method is used on a global and regional scale. Furthermore, the decomposition differentiates the contributions of single demand sectors (food, feed, bioenergy and others) on the dynamics of cropland and agricultural GHG emissions. For the future analysis, data from projections of the Model of Agricultural Production and its Impact on the Environment (MAgPIE) is used, following the middle of the road scenario of the Shared Socio economic Pathways (SSP2) between 1995 and 2105. Focusing on the possible influences of bioenergy on the environmental impacts of agriculture, a baseline and a mitigation scenario are compared varying in the demand of bioenergy and carbon prices for emitted GHGs.

The results show that whilst in the past population growth represent the major driver for agricultural production, it loses its main influence during the 21^{st} century. In the future, bioenergy is identified as the main driver being responsible for more than 50% of cropland expansion in the baseline and 70% in the mitigation scenario. Furthermore, the cultivation of bioenergy crops contributes about 40% to 60% of future N_2O emission increases. Besides bioenergy, the livestock sector also significantly influences agricultural GHG emissions. 40% of CH_4 emissions increases are caused by livestock production. In contrast, improved technological practices in agriculture reduce pressure on both cropland and GHG emissions.

While the production of bioenergy shows definite potential to reduce net GHG emissions by replacing fossil fuels, it has an extreme influence on agricultural GHG emissions and land use changes. Using crops for the provision of energy competes with food production for available resources such as cropland, water and fertilizer. Hence, food security has to be guaranteed before crops are cultivated to produce energy. Shifting diets towards the reduction of animal-based products in emerging and developed economies instead is able to lessen GHG emissions without severe consequences for the global food security.

Zusammenfassung

Landwirtschaftliche Nutzflächen beanspruchen zur Zeit 12% der eisfreien Landflächen. Deren aktuelle Ausdehnung sowie die Produktion landwirtschaftlicher Güter ist für 32% der anthropogenen Treibhausgase verantwortlich (in CO_2-Equivalenz (CO_2e)). In der Vergangenheit waren die wachsende Bevölkerung, der vermehrte Konsum tierischer Nahrungsmittel und technologische Verbesserungen hauptverursachend für die landwirtschaftliche Produktion. In Zunkunft wird zudem Bioenergie einen tragenden Einfluss darauf haben. Jedoch ist das Ausmaß der einzelnen Faktoren ungewiss.

In dieser Arbeit werden die Hauptverusacher steigender landwirtschaftlicher Produktion charakterisiert. Dabei werden sie mit Hilfe einer Kaya-ähnlichen Dekompositionsmethode hinsichtlich ihrer Auswirkung auf Agrarflächenausdehnung und Treibhausgasemissionen auf globaler sowie regionaler Ebene quantifiziert. Die verschiedenen Bedarfskategorien (pflanzliche Nahrung, Futter, Bioenergie und andere) werden in einem weiteren Schritt aufgespalten und deren Einfluss auf die landwirtschaftliche Produktion berechnet. Als Datengrundlage dienen Zukunftsprojektionen des "Model of Agricultural Production and its Impact on the Environment" (MAgPIE) zwischen 1995 und 2105. Zwei Szenarien mit unterschiedliche Politikstrategien werden auf Basis des "middle of the road" Szenario der Shared Socio economic Pathways (SSP2) entwickelt, um den Einfluss von Bioenergie genauer zu analysieren.

Diese Studie zeigt, dass Bevölkerungswachstum, als einer der wichtigsten vergangenen Einflussfaktoren für landwirtschaftliche Produktion, am Ende dieses Jahrhunderts nahezu keine Auswirkung mehr aufweißt. In der Zunkunft ist vor allem Bioenergie für die Expansion von Agrarflächen verantwortlich (etwa 50% bis 70%). Außerdem werden etwa 40% bis 60% der steigenden N_2O-Emissionen durch Bioenergieproduktion verursacht. Neben Bioenergie ist die Produktion tierischer Nahrungsmittel ein weiterer Verursacher von wachsenden Treibhausgasemissionen in der Landwirtschaft (etwa 40% der CH_4-Emissionen stammen aus diesem Sektor). Technologische Verbesserungen können sowohl den Druck auf landwirtschaftliche Flächen als auch auf Emissionen reduzieren.

Durch die Nutzung von Bioenergie können Treibhausgasemissionen im Allgemeinen vermieden werden. Aufgrund der Konkurrenz zur Nahrungsmittelproduktion muss hier jedoch zunächst die globale Nahrungsmittelsicherheit bei gleichbleibendem Preisniveau gewährleistet sein. Im Gegensatz dazu kann ein sinkender Konsum tierischer Nahrungsmittel die Emissionen vermindern, ohne Einfluss auf die Bereitstellung ausreichender Nahrungsmittel und die Gesundheit der gesamten Weltbevölkerung zu nehmen.

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List of Abbreviations

CO_2e	CO_2 equivalent
AFR	Sub-Saharan Africa
CCS	Carbon Capture and Storage
CPA	Centrally Planned Asia including China
DM	Dry matter
EDGAR	Emission Database for Global Atmospheric Research
EMF	Energy Modelling Forum
EUR	Europe including Turkey
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistics
FSU	The Former Soviet Union
GCM	Global Climate Models
GDP	Gross domestic product
GHG	Greenhouse gas
GLO	Global
GTAP	Global Trade Analysis Project
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LAM	Latin America
LPJmL	Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model
MAgPIE	Model of Agricultural Production and its Impact on the Environment
MEA	Middle East/North Africa
NAM	North America
PAO	Pacific OECD including Japan, Australia, New Zealand

PAS	Pacific (or Southeast) Asia
ReMIND-R	Regionalized Model of Investments and Development
SAS	South Asia including India
SRES	Special Report on Emission Scenarios
SSP	Shared Socio-economic Pathways
SSP2	Middle of the Road Scenario of the SSP
UNFPA	United Nations Population Fund

1 Introduction

Current agriculture is responsible for about one third of total anthropogenic greenhouse gas (GHG) emissions (EPA 2006). The emissions drive global warming and increase the risks for extreme weather events like inundations and droughts which can reduce agricultural production quantities severely. Additionally, agriculture causes soil degradation and land use changes (Foley et al. 2011). These changes in land-cover influence biophysical characteristics of the soil and plant cover, destroy natural heritages for animals and plants and emit additional GHGs by reducing carbon sinks (Ramankutty and Foley 1998). Available land for agriculture is limited by the amount of ice-free land and by the need for nature conservation (Foley et al. 2011, Erb et al. 2007). As for now, the influence of agriculture poses a risk for the ecological balance of the earth and by that may increase the potentials for conflicts in human society on multiple levels.

The major aim of agriculture is to serve global food security (Ericksen 2008). Currently there is a large disparity in food consumption standards. More than 900 million people in the developing world suffer from undernourishment (Webb 2010) while, mostly in developed regions, the per capita food demand increases by changing diets towards the consumption of more fat- and protein-rich products (Rosegrant et al. 2001b). Furthermore, bioenergy already uses 1% of global cropland (Gallagher 2008) and is projected to largely increase in the future (Popp et al. 2011, OECD and FAO 2011). Replacing fossil fuels with bioenergy has the potential to reduce GHG emissions as in combination with carbon capture and geologic storage it can lead to a net removal of CO_2 from the atmosphere and to give more independence from fossil resources (Popp et al. 2011, Davis et al. 2011). However, its production competes with food production for land and other resources (Field et al. 2008). Thus, bioenergy might worsen the problem of land degradation, destruction of biodiversity and reduction of carbon stocks by expanding cropland into forests and nature (Gallagher 2008). Clearly, agricultural systems must not over-use existing resources and avoid severe consequences for the environment. To maximize production quantity while protecting the land and keeping GHG emissions as low as possible, sustainable agricultural production is needed (Tilman et al. 2002). To minimize damage resulting from agriculture the increase of croping intensities, the shift of diets and the reduction of waste were discussed in literature as possible solutions (Foley et al. 2011, Godfray et al. 2010b).

The main drivers of agriculture are changes in population, food demand, bioenergy and technological improvements. To implement sustainable agriculture the influence of these drivers needs to be understood in detail. Therefore, they are required to be quantified with respect to the environmental impacts of agriculture such as land use changes and GHG emissions. For historical data, this has successfully been done for land use changes by Huber et al. (2013) and Kastner et al. (2012). However, the influence of these drivers on GHG emissions is poorly understood. Also, future trends are not yet investigated extensively.

This study aims to quantify the importance of drivers showing the largest influence on land use changes and GHG emissions in agriculture. Beside a global historical analysis, two scenarios with different policy strategies (baseline and mitigation) and the global impact as well as regional variations are compared for the future. Further the influence of different demand sectors, namely vegetable food[1], feed for livestock, bioenergy and other crop production are quantified. A Kaya-like decomposition method is used for the analytical characterization. The factors are analyzed in terms of land use changes and emissions resulting from agriculture (namely CO_2, CH_4 and N_2O). The analysis is realized with historical data from FAOSTAT (2011) and EC-JRC/PBL (2011) and future outputs from the Model of Agricultural Production and its Impact to the Environment (MAgPIE) (Schmitz et al. 2012, Popp et al. 2010, Lotze-Campen et al. 2008). The used future scenarios follow the middle of the road scenario of the Shared Socio economic Pathways (SSP2) (O'Neill et al. 2012, Edenhofer et al. 2010b) with the inclusion of projections concerning bioenergy production and carbon prices from the Energy Modeling Forum (EMF) (EMF 2013).

The methodological approach of this study goes back to the 1970's when Ehrlich and Holdren (1971) developed the $I = PAT$ formula to better understand human impacts on the environment. The equation connects influences on the environment (I) with the linear combination of population (P), affluence (A) and technology (T) (Waggoner and Ausubel 2002). Later on, it was widely used as the so called Kaya-identity to quantify the main drivers of CO_2 emissions (Steckel et al. 2011, Raupach and Marland 2007, Albrecht et al. 2002, SRES 2000). $I = PAT$ found less application in the analysis of other environmental impacts that occur in agriculture (Huber et al. 2013, Kastner et al. 2012, Waggoner 1995). In comparison to these decomposition analyzes of land use changes, this study is improved by mainly three aspects. First, it quantifies both past trends as well as future projections. Second, it expands to observe not only land use changes, but also GHG emissions in agriculture. And third, a detailed analysis of the per capita demand is implemented to quantify the impact of single demand categories.

[1] Vegetable food represents all human plant-based food products.

The next chapter gives a literature overview, where the analyzed impacts of agricultural production and their drivers are reviewed in detail. Chapter 3 describes the methods and data sources. An explicit depiction of the model for projections until 2105 (MAgPIE) and the used scenarios for future development (SSP and EMF) is given. Furthermore, the decomposition method is specified analytically. The fourth chapter summarizes the results of the analysis. In Chapter 5, these results are discussed in the current research context concerning scientific literature. Finally, the sixth chapter summarizes the main findings and concludes with an outlook for further research.

2 Literature overview

The following section gives a qualitative overview on the impacts of agriculture and describes their drivers. First, the historical changes and future trends of the impacts due to agricultural production in terms of area expansion and GHG emissions are described, among others. Second, the drivers for these impacts (namely population, per capita crop demand, bioenergy, area intensity[1] and emission factors[2]) are demonstrated. Bioenergy, as one part of per capita demand, is specified separately because of its new relevance in the future. To describe the temporal development of a certain impact or driver, first a review of current and past literature is given and then it is placed in the context of the values for future projections used in the present analysis.

For this study, future developments are represented exemplary by the SSP scenario family (O'Neill et al. 2012, Chateau 2012, Edenhofer et al. 2010b). The SSP are long-term future scenarios used in climate impact research and can be seen as the follower of the well known Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC). Two middle of the road SSP scenarios (SSP2) are used for this analysis provided by the EMF, one SSP2 baseline and one SSP2 mitigation scenario. The mitigation scenario keeps GHG emissions in the atmosphere under 450 ppm until the end of the century. A detailed description of the scenarios is given in Chapter 3.

2.1 Impacts of agricultural production

Agricultural production has various impacts on the environment. Cropland expands to serve global food and energy demand, thereby land (with high biodiversity and forests) is cleared and the carbon stored in the natural biomass is released in the form of CO_2 emissions. Due to higher livestock production and the use of fertilizers even more GHG emissions are produced - especially CH_4 and N_2O emissions. Additionally, water, soil and air are contaminated among other things due to the nutrient losses from fertilization and manure management.

[1] Area intensity represents the quotient of cropland and crop production or demand, the reciprocal of yield.
[2] Emission factors describe the amount of GHG emitted by a certain agricultural activity.

2.1.1 Land use expansion

Since the beginning of human settlement, agricultural land was mostly used for the production of food crops while animals were fed with biomass from pasture and food waste. Over time, more and more food was needed for the growing population. Therefore, land used for crop production expanded (Hazell and Wood 2008). With the increasing consumption of animal products, livestock management became centralized and industrialized, in a way that pastures alone could not serve the entire feed needed for livestock production. Cropland began to be used to produce feed and expanded into areas abound in biodiversity and the carbon stocks in forests and other natural vegetation were released (Watson et al. 2005). In the past decade and even more so in the future, the production of bioenergy crops puts additional pressure on land (Ehrlich and Pringle 2008).

According to the declaration of the Food and Agriculture Organization of the United Nations (FAO) (FAOSTAT 2011) agricultural land can be divided into three different types, arable land (annual cultivation, mainly cropland), pasture (managed grasslands for livestock production) and permanent cropland (vineyards and fruit plantation). In this study, the focus lies on the examination of arable land and is named cropland.

Between 1700 and 1980, cropland expanded from 2% to 11% of total ice-free land surface while the expansion rate mounted within this period of time (Waggoner 1995). From 1961 to 2005, cropland rose by about 11.5% to the current 12% of ice-free land used as cropland (FAOSTAT 2011, Foley et al. 2011) and 26% used as pasture (Foley et al. 2011). In total, for agricultural production, including cropland, managed grasslands, permanent cropland and agro-forests, about 40% to 50% of global land area is currently used (IPCC 2007: p. 499). This land expands into the other types of land to follow global crop demand.

The potential of physical arable land expansion is about 31% of the ice-free land cover for cropland and 33% for pasture (DeVries et al. 1995). Suitable land for crop cultivation depend on industrialization, urbanization and infrastructural development and on how land degradation, desertification as well as climate change develop (Gerbens-Leenes and Nonhebel 2002, Oldeman et al. 1999). Land is not only limited by physical boundaries, such as the total amount of ice-free land surface, but also by the necessity to spare land for nature conservation and carbon sequestration (Foley et al. 2011, Rockström 2009, Erb et al. 2007).

In the used future projections, cropland expands to 1500 or 1800 million hectares in 2055 depending on the underlying scenario (see Figure 2.1).

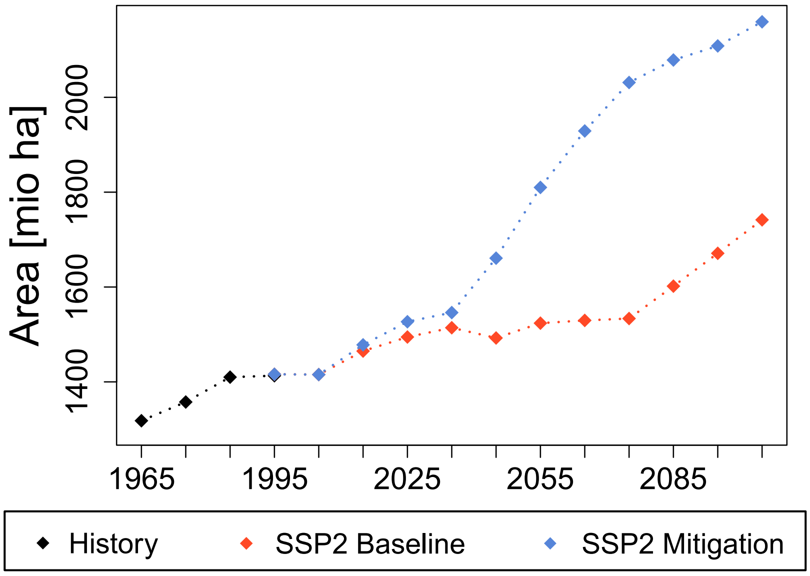

Figure 2.1 – Global cropland in history (FAOSTAT 2011) and for future projections of MAgPIE with underlying SSP2 scenarios and different policy strategies.

2.1.2 Greenhouse gas emissions

Climate change might be one of the biggest challenges for future generations. By emitting GHG emissions (mainly CO_2, CH_4 and N_2O), global food systems or rather agricultural production contributes its part of environmental change (Ericksen 2008). The following paragraph describes the sources of these emissions. Moreover, the relevance of GHG emissions in agriculture in comparison to other sectors and its future development is depicted.

CH_4 emissions in agriculture mostly stem from livestock production (manure management and enteric fermentation) and rice cultivation when organic materials decompose under oxygen-deprived conditions (Olesen et al. 2006, Mosier et al. 1998). N_2O emissions often occur as a consequence of the use of inorganic fertilizers and losses from manure or crop residues (Mosier et al. 1998). This input of reactive nitrogen into soil matter causes nitrification and denitrification, which is responsible for N_2O emissions. CO_2 emissions are not only produced by the use of engines in agriculture, but also by the conversion of vegetation with high carbon content into cropland. Soils and plant biomass store about three times as much carbon than the atmosphere (Fargione et al. 2008). The carbon stored in the soil and the biomass on the land is partly released into the atmosphere. Therefore, GHG emissions are influenced by every land use change. In most cases, only a smaller amount of carbon, taken out of the atmosphere, is re-incorporated into the new biomass growing on the land. Usually the potential of carbon storage in the transformed land is lower than before (Van Der Werf et al. 2009, Lal 2003, Paustian et al. 2000). CO_2 and N_2O emissions in agriculture are also released from microbial decay or the burning of plant litter and organic soil matter (Janzen 2004).

Excluding emissions from land use change, agricultural production is responsible for about 10 - 20% of total anthropogenic GHG emissions (Burney et al. 2010, Foresight 2009, Stehfest et al. 2009, Cole et al. 1997). Figure 2.2 shows this amount of emissions (given in the latest IPCC report, Working Group III) in comparison to other sectors (IPCC 2007: p. 29). Changes of land use account for about 6 to 17% additional emissions (Friel et al. 2009). In total, EPA (2006) attributed 32% of global GHG emissions to agricultural sources including land use change in 2000.

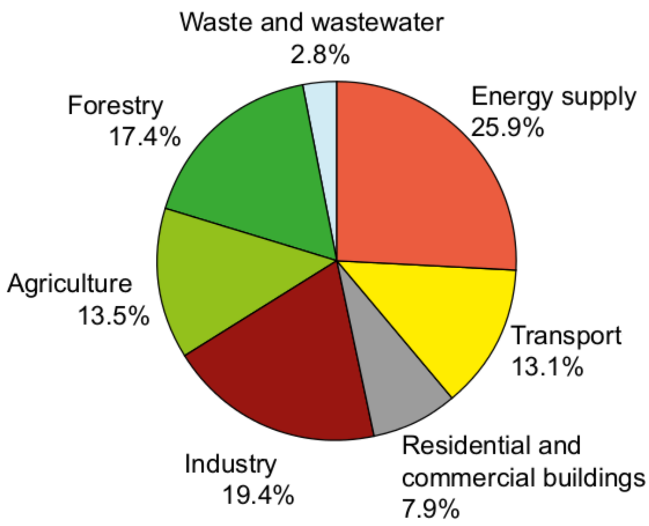

Figure 2.2 – Global GHG emissions by sector in 2004, taken from (IPCC 2007: p. 29).

The most important GHG emissions are CO_2 (72.2%), CH_4 (19%) and N_2O (8.8%) (see Figure 2.3, numbers are from 2005). The most important GHG emissions in agricultural production systems are CO_2 (35.5%), CH_4 (43.7%) and N_2O (20.8%) (in percentage of total GHG emissions in agriculture, see Figure 2.4) (EC-JRC/PBL 2011). 50% of global methane

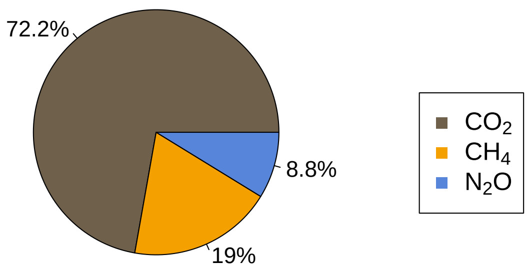

Figure 2.3 – Total global GHG emissions in 2005 (EC-JRC/PBL 2011).

emissions and 60% of global N_2O emissions result from agricultural production (IPCC 2007: p. 63). Global methane and N_2O emissions from agriculture increased by about 17% between 1990 and 2005 (IPCC 2007: p. 499) and global CO_2 emissions by about 10% in the same period of time (EC-JRC/PBL 2011).

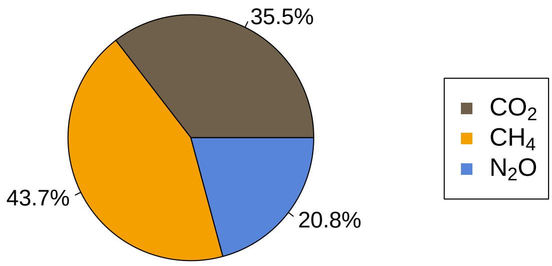

Figure 2.4 – Global GHG emissions in agriculture in 2005 (EC-JRC/PBL 2011).

In the future, an expansion of cropland and pastures into intact forests and grasslands leads to an increase of carbon dioxide emission whilst nature sinks tail off (Canadell et al. 2007, Gitz and Ciais 2004). An increase of CH_4 and N_2O emissions is also probable. In the SSP2, total GHG emissions from agriculture peak in the middle of the century in the mitigation scenario and increase until the end of the century in the baseline scenario. A drastic emission increase from 2035 onwards can be seen especially in the SSP2 mitigation scenario, because of the intensive use of bioenergy and reach a maximum of more than 18 billion tons (see Figure 2.5). In particular, in this scenario a shift of GHG emissions from the energy to the agricultural sector takes place to provide electricity and fuel.

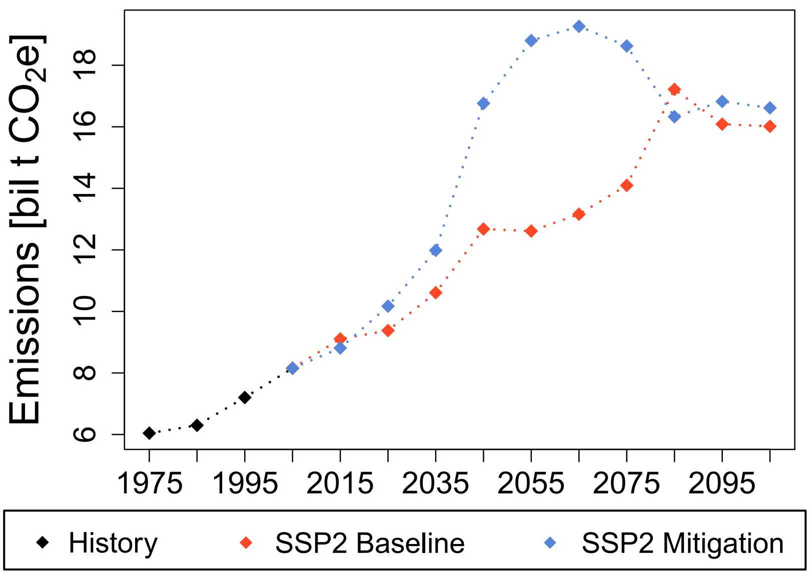

Figure 2.5 – Global GHG emissions in history (EC-JRC/PBL 2011) and for future projections of MAgPIE with underlying SSP2 scenarios and different policy strategies.

2.1.3 Further impacts

Further impacts of agricultural production are water, soil and air pollution as well as losses of biodiversity. A short overview on these impacts is given here, but they are not quantified in the further analysis.

Water is taken out of the system to irrigate cropland and only a part of it is turned back. What is returned to the water cycle is often polluted due to the over-use of fertilizers and pesticides as well as due to livestock production and salinization. Manure residues add harmful substances including heavy metal to ground- and standing waters. An over-use of nutrients leads to an eutrophication of global water stocks and in this way to a disturbance of the ecosystem (Rozemeijer and Broers 2007). High concentrations of harmful substances in drinking water are dangerous to human health.

Another big problem resulting from agricultural production is soil erosion. It is caused by ground-salinization and contamination of soils with the losses of chemical fertilizers, pesticides and heavy metals because of changes in the soil composition (Velthof et al. 2011). The loss of organic soil matter due to pollution reduces the natural soil layer, which gives a negative impact to nutrient enrichment of the ground. On the other hand, an over-nutrition can lead to an overtake of one species and therefore a displacement of others. This might result for changes in plant diversity (Velthof et al. 2011).

Next to atmospheric pollution, the over-use of fertilizers and pesticides can result for further air pollution. Hereby the main polluters are ammonia, Mono-nitrogen oxides and ground level ozone, which can affect human health (Moldanová et al. 2011).

Biodiversity losses result partly from land use change as well as soil, air and water pollution but also from climate change and therefore indirectly from increasing GHG emissions (Sala 2000).

2.2 Past and future drivers of agricultural systems

Agricultural production is mostly driven by population and per capita crop demand while improvements in yields and for emission factors can reduce its impacts.

2.2.1 Population

One of the most obvious drivers of agricultural production is population. The more people are living on the planet, the more food and energy is needed. In 2000, world population counted nearly 7 billion with a growing rate of about 1.3% per year (UNFPA 2012, Kates 2000).

In the last century, the population more than tripled (Ramankutty et al. 2002) while in the last 50 years more than a doubling of the population took place (Smith et al. 2010, Burney et al. 2010). Historically, the maximum population growth rate was 2.1% per year in the early 1960s (Kates 2000).

There are projections for the future that the population grows to more than 9 billion in 2050 (UN 2012, Foresight 2009, World Bank Group 2007) and declines afterwards (Godfray et al. 2010a). The United Nations Population Fund (UNFPA) predicted that over 10 billion people live on the planet by 2100 (UNFPA 2012, FAO 2011). Lutz et al. (1997) found a projection range of population in 2050 between 8.1 and 11.9 billion. Projections for 2100 have a bigger range because of higher uncertainties for a longer projection, the population lies between 5.5 and 14 billion (Lutz and K. C. 2010). However, with a probability of 80 - 90% a population peak is reached before 2100 (Lutz et al. 2001).

Figure 2.6 shows the development of population in the past and for the future with the middle of the road scenario (SSP2) in comparison to the two scenarios (SSP1 and SSP3) in SSP which show the highest and lowest value. In SSP2 population is projected to stay below 10 billion until 2100 and reaches 9.3 billion in 2050 (IIASA 2013).

2.2.2 Per capita crop demand

Current global crop production amounts to about 10.6 billion tons of dry matter per year (2010). It tripled in the last decades from only 3.5 billion tons in 1961 (FAOSTAT 2011).

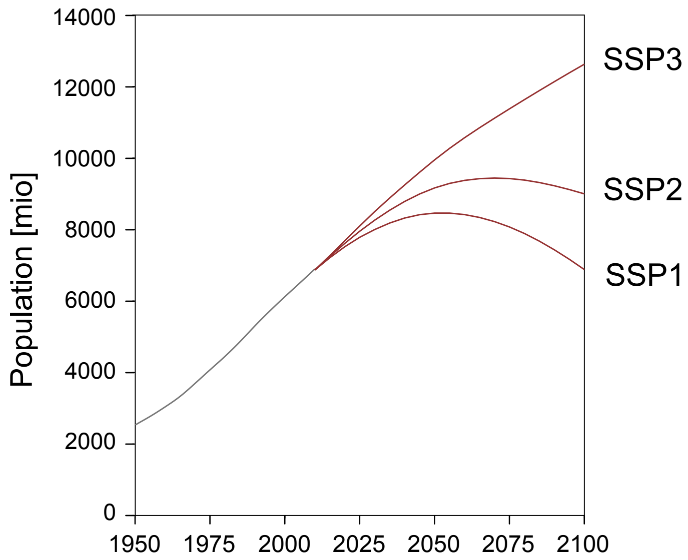

Figure 2.6 – Population development in history and for future SSP projections, adapted from (IIASA 2013).

Crop demand can be divided into different sectors. The main sectors are vegetable food production, feed for livestock, bioenergy, materials, seeds and waste. Currently, about 62% of crop biomass production is allocated to human vegetable food, while about 35% is produced for animal feed and 3% for bioenergy, seed and other materials (Foley et al. 2011). Including pasture only about 12% of economically used plant biomass is used as vegetable food while nearly 60% is used as livestock feed (Krausmann et al. 2008). The remaining part is used for material or as fuel (Krausmann et al. 2008). One driving factor of total crop demand is population, which was discussed in the previous section. In this section, the per capita demand for the different production sectors is analyzed. Because of the special focus on bioenergy in this work, the energy sector (regarding bioenergy) is discussed extensively in Section 2.2.3.

Total crop demand is projected to increase until the end of the century. In the SSP2 baseline scenario, the yearly production of crops increases to about 16 billion tons of dry matter in 2105. With the goal to keep the concentration of greenhouse gases in the atmosphere below 450 ppm it increases to more than 34 billion tons by the end of the century (see Figure 2.7).

Food demand: Per capita food demand (including vegetable food as well as animal based groceries as an intake and the waste on a household level) is mainly driven by income, demography, urbanization, education and culture (Bodirsky et al. 2012b, Parfitt et al. 2010). On low income levels food consumption rises strongly with increasing wealth (Bodirsky

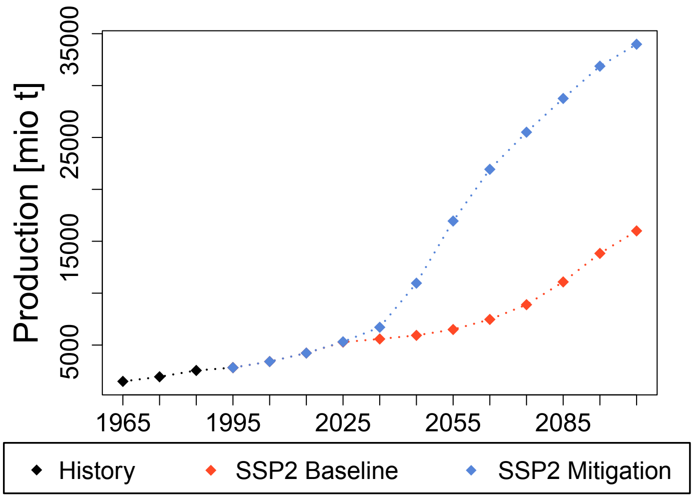

Figure 2.7 – Global crop production in history (FAOSTAT 2011) and for future projections of MAgPIE with underlying SSP2 scenarios and different policy strategies.

et al. 2012b). Moreover, the diet shifts towards more refined high-value products which often require large amounts of resources (Godfray et al. 2010b, Kearney 2010, Gerbens-Leenes and Nonhebel 2002). High-value food includes animal based products as well as protein- and fat-rich vegetable products.

History showed a continuous increase in per capita food demand. Mueller and Schmidhuber (2008) observed that in developed countries per capita food demand increased by about 15% while in developing countries a rise of 50% took place. Another study found that total food production nearly tripled between 1961 and 2005 while per capita food demand increased by only about 20% (Hazell and Wood 2008). Green et al. (2005) estimated that with the currently used cropland, enough food could be produced for twice the world population if everybody would follow a plant-based diet. Future prospects have high uncertainties, but a decrease of per capita food demand is improbable (Tilman et al. 2002, Delgado et al. 1998). DeFries and Rosenzweig (2010) projected a 50% increase in food demand until 2050 because of a rising per capita consumption.

A meat based consumption requires around six times as much crops than a wheat based consumption (Gerbens-Leenes and Nonhebel 2002). Additionally, pastures are used to feed animals. These lands are not always suitable for cropping. Still, the share of livestock products strongly determine total crop demand (Bodirsky et al. 2012b, Stehfest et al. 2009). It rose from 15% in 1961 to 17% in 2005 (FAOSTAT 2012). In numbers, livestock product demand increased from 25.5 kg/capita/yr in 1967 to 36 kg/capita/yr in 1997 (Rosegrant et al. 2001b).

A change in diets towards a higher consumption of meat is probable (Bodirsky et al. 2012b, Tilman et al. 2002). This change is partly attributed to the increase of average income.

An increase of about 57% in meat consumption in 2020 compared to 1997 is forecast by Rosegrant et al. (2001a). The share of animal products in food production may increase by 70 - 90% till 2050 (Rockström et al. 2007).

Because of the metabolic requirements of human bodies, and hence a limitation of the possible average food intake, a portion of per capita food demand actually gets wasted. Smil (2000) estimated that plausible regional intake rates in developed regions lie between 2100 and 2300 kcal per capita and day. An increase of per capita food demand over this level can be seen as an increase in household waste. If per capita food demand is higher in the future, waste also increases (Bodirsky et al. 2012b).

About 30% of global crop production currently gets wasted (1.3 billion tons per year) (Gustavson and Cederberg 2011). Kummu et al. (2012) estimated that about 45% of this is wasted on the consumption level. Waste is driven by income and also depends on demography, culture and education. On the household level wasting mainly takes place in high-income countries (Gustavson and Cederberg 2011). In industrialized countries per capita food waste on the consumer level is about ten times higher than in developing countries in Sub-Saharan Africa and South/Southeast Asia (Gustavson and Cederberg 2011). Next to income, the growth of single household, the aging population and low prices are drivers for this kind of waste (Parfitt et al. 2010). The attitude of wasting also depends on culture, while in general it can be noticed that young people waste more than old people (Parfitt et al. 2010).

Other demand: Other crop demand is mainly the use as material, seed and waste on a production level.

55% of the food waste are crops getting lost during production and processing. In low-income countries this effect is mostly driven by the missing infrastructure and technologies for storage and cooling (Gustavson and Cederberg 2011). In industrialized countries mostly regulations, standards and trade are a reason for this kind of waste (Parfitt et al. 2010). In the future, waste reduction is probable as technology in the developing world achieves a higher standard. Due to the growing population and therefore a growing demand for crops, waste reduction would be an easy way to achieve higher production levels (Parfitt et al. 2010).

The crop demand for materials (e.g. bioplastics, fabrics and other industrial products) largely depends on income and culture. The crop demand for seed depends on the crops cultivated on arable lands. The demand of crops for material use and seed amounts to less than 2% (Foley et al. 2011) of total crop demand and can be expected to have a similar share in the future.

2.2.3 Bioenergy as a new pressure for crop demand

The main drivers for bioenergy are the per capita energy demand and the share of bioenergy in the energy mix. Both parameters largely depend on climate mitigation targets, while the share of bioenergy in the energy mix is additionally influenced by the availability of fossil fuels and the instability of its price (Tao and Aden 2009). Furthermore, the production of bioenergy is limited by natural resources (water and land availability) and it competes with food production and other use of crops (Ogle et al. 2007).

Depending on sustainability aspects during the production of bioenergy, it can have positive and negative environmental impacts (Schubert et al. 2010). The consequences for the environment not only depend on the feedstock but also on the geographical location relating to transportation as well as the conversion of land (Davis et al. 2011). The biomass produced for bioenergy takes carbon from the atmosphere, but the plants may replace other vegetation, which would instead grow on the land (Haberl et al. 2012). Moreover, the amount of carbon emitted into the atmosphere by driving a bioenergy-engined car has the same amount as by driving with fossil power sources (Haberl et al. 2012). However, it does not release the carbon which was stored over millions of years such as fossil fuels do. The idea of replacing fossil fuels with bioenergy in a competitive way came up in the 1970s because of high oil prices (Naik et al. 2010, Schlegel and Kaphengst 2007). Especially in combination with carbon capture and storage (CCS), it has the potential to achieve the 2°C target of global warming (Edenhofer et al. 2010a). Even if health and safety risks might occur by the use of CCS technologies (Fogarty and McCally 2010), it is used as a promising mitigation option in future projections to produce negative GHG emissions in combination with bioenergy (e.g. Popp et al. 2011).

Replacing fossil fuels with bioenergy does not only have the potential to reduce GHG emissions, but it also increases opportunities, in particular for countries with limited oil reserves, to become more independent concerning the energy sector (Davis et al. 2011). Furthermore, it gives the possibility to boost rural areas, notable in developing countries, and supports agriculture (Sims et al. 2008). Another plus of bioenergy, in contrast to other renewable sources such as wind and solar energy, is its potential to drive existing engines and the possibility to easily store and transport the energy carriers and use them at the places where they are needed.

There is also a negative side of the impacts of bioenergy production, namely the competition with food production, which may lead to increasing food prices (Naik et al. 2010, Banse et al. 2008) and therefore undernourishment (Gallagher 2008). Bioenergy can also boost managed monoculture, water and soil contamination, and causes the loss of biodiversity because an intensified or extended land use is necessary (Field et al. 2008). Haberl et al. (2012) concluded that bioenergy can only result for negative emissions if waste or residues are used to produce energy. However, environmental impacts largely depend on the feedstock, which is classified to first and second generation bioenergy.

Used feedstock are oil-, starch- and sugar- rich plants for first generation and lignocellulosic biomass for second generation bioenergy. First generation biofuels are already commercial and cost-efficient options to drive engines (Naik et al. 2010). These include biodiesel, ethanol and biogas. They already improve domestic energy security, but their benefits for the reduction of GHG emissions are limited (Sims et al. 2008) and depend on the used land, its location and the sustainability of feedstock production (Davis et al. 2011, Banse et al. 2008). First generation biofuels can be used in a mixture with conventional fuels and they can be burned in existing combustion engines used in most vehicles. Also the distribution can be achieved through existing infrastructure. However, the impact on biodiversity and the use of fertile land is high. Therefore, it is recommended to look for alternatives with lower impact on the environment. Lignocellulosic feedstock (including fast growing trees and grasses like eucalyptus, poplar, willow, elephant grass and switchgrass), known as second generation bioenergy, has the potential to produce a high amount of biomass in a short time with a low nutritional requirement (Sims et al. 2008). Less fertile soil can be used and the plants do not need perfect climate conditions to grow (Naik et al. 2010, Schubert et al. 2010). Feedstock for second generation biofuels is cheap, abundant and a non-food resource. Currently, the technologies to produce energy out of lignocellulostic materials are, even with high oil prices, not economical because the costs for the transformation of the biomass into liquid or gaseous fuels are high. To achieve the possibility of a more competitive capacity, feedstock must be produced more efficiently and process optimization should lead to higher energy or heat outputs (Sims et al. 2008). There is hope to develop better technologies and produce energy in a cost-efficient way, but success is not guaranteed. (Havlík et al. 2011, Naik et al. 2010, Banse et al. 2008, Gallagher 2008)

In the last decade, first generation biofuel production (biodiesel and ethanol) grew rapidly (Banse et al. 2008). Currently, the amount of total crops used to produce bioenergy adds up to 42.5 million tons, which stands for 1.1% of total crop production. The bioenergy share of the global energy production is about 10.2% (numbers from 2008 - total demand 492 EJ) (SREEN 2012). This value includes all energy produced with biomass. Only a small share comes from crops produced on cropland, the rest is generated with wood, waste and other resources. Figure 2.8 shows the energy mix in 2008 referring to the source as percentage of total energy.

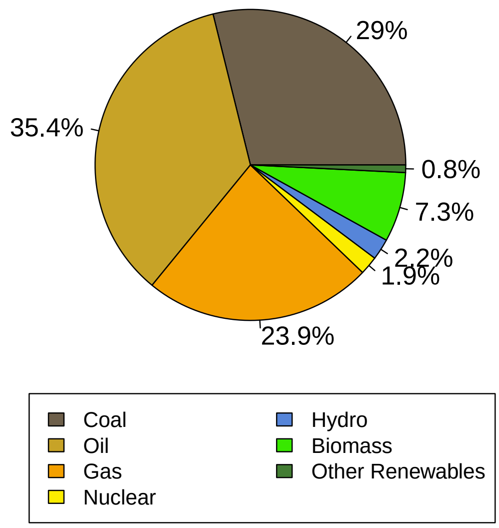

Figure 2.8 – Share of energy sources in percent of total energy demand in 2010 (Luderer et al. 2012).

Future proposed potentials of bioenergy range between less than 100 and 1000 EJ/yr depending on the underlying climate and energy scenario (Popp et al. 2011). Sustainable agriculture is necessary to secure food availability and to protect biodiversity. Under these conditions and the use of CCS, Beringer et al. (2011) estimated the potential of bioenergy to be about 130 - 270 EJ/yr (about 15 - 30% of total energy demand, which lies at about 850 EJ (Mueller and Schmidhuber 2008)) by 2050. In a "food first" scenario bioenergy potentials are assessed lower (64 - 161 EJ/yr) and depend on assumptions in regard to diets, yields and climate (Haberl et al. 2011). Future projected potentials also include second generation biofuels and require a development of technologies in this sector.

With an underlying SSP2 scenario, the Regionalized Model of Investments and Development (ReMIND-R) projected the use of 52.5 EJ bioenergy per year in 2050, which is about 7.8% of total energy demand in this year and about 226.2 EJ/yr in 2100, which is about 13.1% of total energy demand (see Figure 2.9) (Luderer et al. 2012).

In comparison to the above mentioned potentials of bioenergy in the future, the energy content of current produced biomass (all kind of crops, used as food, feed, bioenergy and others) is about 230 EJ/yr (Haberl et al. 2012). If ReMIND-R projections come true, approximately double the amount of biomass has to be produced just to serve the additional demand of bioenergy by the end of the century. Hence bioenergy is one of the main drivers for future agriculture and a competitor for food production. Depending on how biomass for the production of energy is cultivated, the world is reaching a food, energy, environment trilema (Tilman et al. 2009).

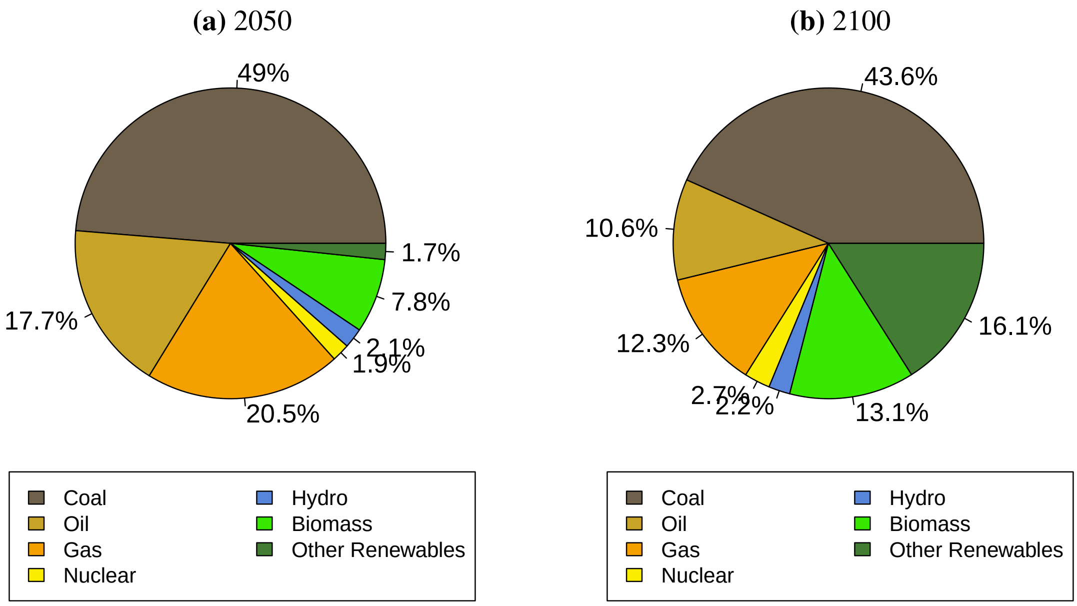

Figure 2.9 – Share of energy sources in percent of total energy demand in 2050 and 2100 (Luderer et al. 2012).

2.2.4 Yield increasing technological change

In the last 50 years, crop production more than tripled (FAOSTAT 2011). Besides land expansion, technological improvements and better knowledge of practice lead to a more extensive cultivation and therefore higher yields to secure food availability (FAO 2011, 2012). Yield increases can be seen as land savings. The rapid agricultural development that took place in the second half of the 20th century is called "Green Revolution". Major fields of technological advancement were irrigation management, use of pesticides and nitrogen or phosphorus fertilizers as well as breeding higher yields. But extensive or inadequate use of pesticides and fertilizers also triggered some environmental damage, such as soil degradation, chemical pollution and soil salinization (Evenson and Gollin 2003, Tilman et al. 2001). In the past, some practices of technology intensification had damaging impacts on the environment. Hence there is a need for sustainable agricultural methods, which protect biodiversity and land (Tilman et al. 2002).

From 1961 to 2000, yields grew with a yearly rate of 1.51% (Ewert et al. 2005). The observed total changes were 135% between 1961 and 2005 (Burney et al. 2010). During the Green Revolution a productivity growth can be summarized as positive for decreasing hunger (Evenson and Gollin 2003). The increasing rate of yields declined in the last decade of the past century. Calderini and Slafer (1998) concluded that the maximum might be reached soon. Another analysis came to the result that there is no significant decrease of yield growth in most of the countries (less than 10% of global harvested area) (Hafner 2003) and that there are no indications for an upper limit of production (Dietrich 2011).

Ewert et al. (2005) estimated future changes in yields to range between 25% and 163% until 2080 depending on climate scenarios. Improvements take place by several actions - higher-yielding breeds, increase of the efficiency of phosphorus-, nitrogen- and water-use and better disease, insect and pest control (FAO 2010, Tilman et al. 2002). Historical development of yields and future SSP2 projections as they are used in the following analysis are shown in Figure 2.10.

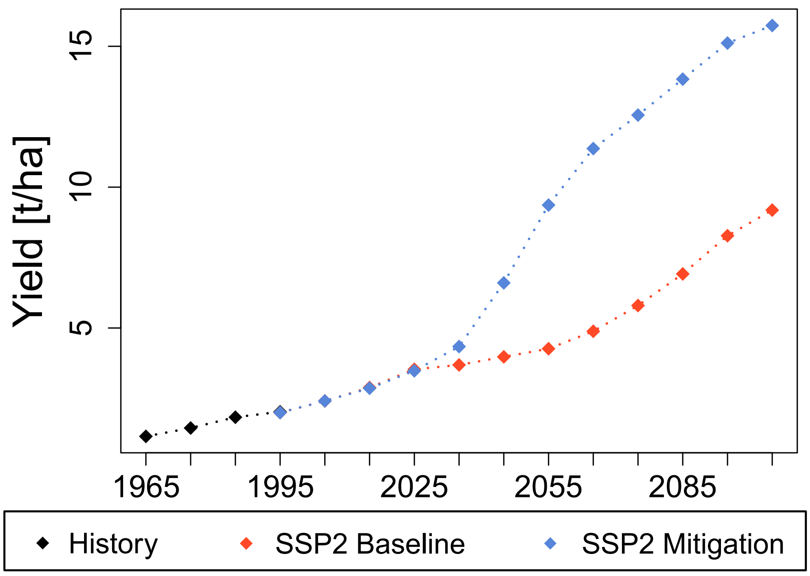

Figure 2.10 – Global yield development in history (FAOSTAT 2011) and for future projections of MAgPIE with underlying SSP2 scenarios and different policy strategies.

2.2.5 Emission factor

The emission factors depend on the source of emissions. They are defined as the average amount of a certain GHG emission relating to a single activity. The IPCC developed guidelines to better estimate national anthropogenic GHG emissions, where certain emission factors were analyzed (Eggleston et al. 2006, IPCC 1996)

CH_4-related emission factors are mostly influenced by livestock management and rice cultivation. The amount of methane released due to enteric fermentation depends on the alimentation of the animals and is from importance for especially ruminant animals like cattle, sheep and goat. CH_4 emissions due to manure management result from large numbers of animals living on little spaces (IPCC 1996). Emissions resulting from rice cultivation can be minimized by an optimized management of water, fertilizer and production cycle. It further depends on soil and product characteristics and climate (IPCC 1996). The N_2O emission factors are mostly related to the use of organic and inorganic fertilizers. If it comes to an over-use of nutrients, which plants cannot take up, the residues of the fertilization react with oxygen and are partly emitted to the atmosphere. Thereby a nutrient-orientated management, which closely regulates timing, placing and quantity of fertilization, can reduce emissions (Eggleston et al. 2006). For CO_2 the emission factor is related to the carbon content of the transformed land and to the amount of biomass burned directly on the fields (IPCC 1996).

3 Data and methods

In this chapter first the sources of used data are described and the used future scenarios for the calculations are depicted. The detailed decomposition method then is shown analytically.

3.1 Data

Historical data is taken from the FAO Statistical database (FAOSTAT 2011) and the Emission Database for Global Atmospheric Research (EDGAR) (EC-JRC/PBL 2011). To generate data for future agricultural production systems a programming land use model (MAgPIE) (Popp et al. 2012, Schmitz et al. 2012, Popp et al. 2010, Lotze-Campen et al. 2008), with underlying scenario assumptions from the EMF (EMF 2013) and from SSP2 (O'Neill et al. 2012, Edenhofer et al. 2010b), is used.

Models are important for science to describe processes in a simplified way and to make prognoses for the future (Sarkar et al. 2006). They are restricted images of their original, where relevant aspects of the system are included. "All components and processes of the original Earth system are replaced by mathematical representatives as accurate as our evolving knowledge allows" (Schellnhuber 1999). Models allow us to project future developments as they use processes and experiences of the past. However, the future projections only show possible developments and largely depend on economic, biophysical and demographic inputs.

3.1.1 Data sets and sources

For the analysis historical data from the FAO Statistics (FAOSTAT 2011) for agricultural values (cropland, crop production, crop demand), data from the International Institute for Applied Systems Analysis (IIASA) for population (IIASA 2013) and data from EDGAR for emissions in agriculture (EC-JRC/PBL 2011) is used. For future projections data from MAgPIE is used for agricultural values and emissions, while population projections are given by the SSP2 scenario. Materials, seeds and waste are combined in “others” because they have respectively small values for demand and production, and the focus does not lie on these production categories in this work. For all demand and production values constant dry matter shares for the different crop sectors to calculate the given FAO data (in wet matter) into dry matter (DM) are used.

All historical data is available in yearly time steps on a global scale. The projected future data is given in ten-year time steps on a global as well as on a regional scale for the ten world regions of MAgPIE. Table 3.1 compiles all the used variables with units, symbols and sources for historical as well as future data.

Some data taken from the model is not in the needed format, so additional assumptions have been made in order to provide it: The amount of crop production Pr_k^i is not given for the different categories k (food, feed, bioenergy and others) but rather for 18 crop types i. The demand D_k^i on the other side is given for both the certain crop type and for each category. All traded crops $Tr^i = Pr^i - D^i$ are divided in imports Im^i ($Tr^i > 0$) and exports Ex^i ($Tr^i < 0$) for each crop type. For importing regions, the values for crop production of each category are estimated by dividing imported Im^i crops of certain crop types into the share of the particular demand category

$$P_k^i = D_k^i + Im^i \cdot \frac{D_k^i}{\sum_k D_k^i}. \tag{3.1}$$

In exporting regions, the production for each category Pr_k^i is assumed by dividing the exported crops Ex^i into the share of a certain category of global imported crops and subtract it from the demand in a certain region

$$P_k^i = D_k^i - Ex^i \cdot \frac{Im_k^i}{Im_{k,glob}^i}. \tag{3.2}$$

3.1.2 MAgPIE model description

MAgPIE is a nonlinear mathematical programming model for land use (Popp et al. 2012, Lotze-Campen et al. 2008). It is coupled to the Lund-Potsdam-Jena dynamic global vegetation model with managed Lands (LPJmL) (Bondeau et al. 2007, Sitch et al. 2003) and ReMIND-R (Leimbach et al. 2009). The model simulates the most important land dynamics on a global and regional scale (Bodirsky et al. 2012a, Lotze-Campen et al. 2008). It contains

	Symbol	Unit	Source historic	Source projections
Cropland	A	[10^6 ha]	FAOSTAT	MAgPIE
Population	P	[10^6]	IIASA	SSP2
Crop production	Pr	[10^6 t] DM	FAOSTAT	MAgPIE
Food production	Pr_{food}	[10^6 t] DM	FAOSTAT	MAgPIE
Feed production	Pr_{feed}	[10^6 t] DM	FAOSTAT	MAgPIE
Bioenergy crop production	Pr_{bio}	[10^6 t] DM	FAOSTAT	MAgPIE
Other crop production	Pr_{others}	[10^6 t] DM	FAOSTAT	MAgPIE
Crop demand	D	[10^6 t] DM	FAOSTAT	MAgPIE
Food demand	D_{food}	[10^6 t] DM	FAOSTAT	MAgPIE
Feed demand	D_{feed}	[10^6 t] DM	FAOSTAT	MAgPIE
Bioenergy crop demand	D_{bio}	[10^6 t] DM	FAOSTAT	MAgPIE
Other demand	D_{others}	[10^6 t] DM	FAOSTAT	MAgPIE
Demand of Livestock products	D_{ls}	[10^6 t] DM	FAOSTAT	MAgPIE
CO_2 emissions	CO_2	[10^6 t CO_2e]	EDGAR	MAgPIE
CH_4 emissions	CH_4	[10^6 t CO_2e]	EDGAR	MAgPIE
CH_4 emissions for livestock management	CH_4^{LS}	[10^6 t CO_2e]	EDGAR	MAgPIE
N_2O emissions	N_2O	[10^6 t CO_2e]	EDGAR	MAgPIE
N_2O emissions for livestock management	N_2O^{LS}	[10^6 t CO_2e]	EDGAR	MAgPIE

Table 3.1 – Used variables with units, symbols and sources for past and future data.

18 crop and five livestock production activities in 10 world regions (see Figure 3.1, AFR = Sub-Saharan Africa, CPA = Centrally Planned Asia including China, EUR = Europe including Turkey, FSU = the Former Soviet Union, LAM = Latin America, MEA = , NAM = North America, PAO = Pacific OECD including Japan, Australia, New Zealand, PAS = Pacific (or Southeast) Asia, SAS = South Asia including India).

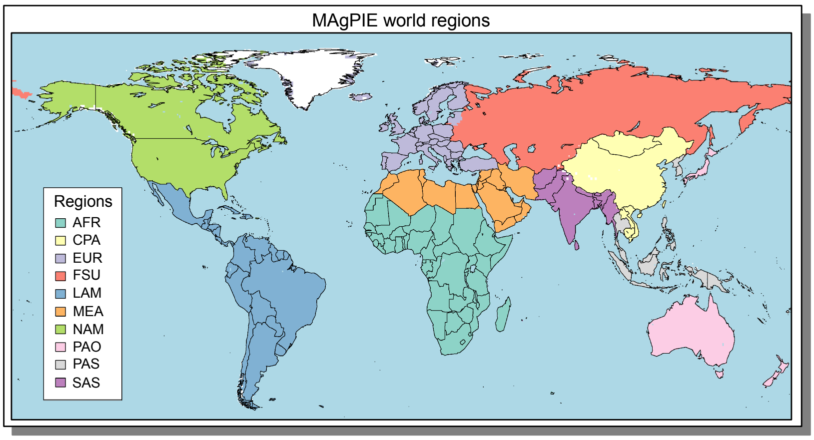

Figure 3.1 – MAgPIE world regions, taken from (Schmitz et al. 2012).

The model takes into account the major dynamics in the agricultural sector such as trade, technological progress and land allocation (according to yields, costs and water resources). It is an optimization model with the objective function to minimize total costs of production under a given crop demand. As shown in Figure 3.2, the model is not only coupled to a grid-based dynamic vegetation model (LPJmL) and the global energy-economy-climate model ReMIND-R, but also receives data from databases like FAOSTAT and the Global Trade Analysis Project (GTAP) (FAOSTAT 2012, McDougall et al. 1998), as well as via LPJmL from global climate models (GCM).

On the supply side, activities are based on clustered grid-cells ($0.5^\circ \times 0.5^\circ$-cells) while on the demand side, data is aggregated on a regional scale. The regional demand depends on the demand for food, feed, bioenergy and others (such as materials, seeds and waste), based on the taxonomy of the FAO food balance sheets (FAOSTAT 2012). The food demand is estimated, based on the use of exogenous inputs of population and income developments (Bodirsky et al. 2012b). Feed demand depends on livestock production with different feed baskets for the regions and livestock categories (Weindl 2010). Crop demand for bioenergy production is derived by ReMIND-R (Leimbach et al. 2009). ReMIND-R couples an intertemporal economic growth model with a detailed energy system model and a climate system model on a multi-regional scale (Popp et al. 2012). The coupling between MAgPIE and ReMIND-R is based on bioenergy production and carbon costs. Thereby the bioenergy demand and the prices for carbon emissions are taken from ReMIND-R. On the other hand, MAgPIE gives

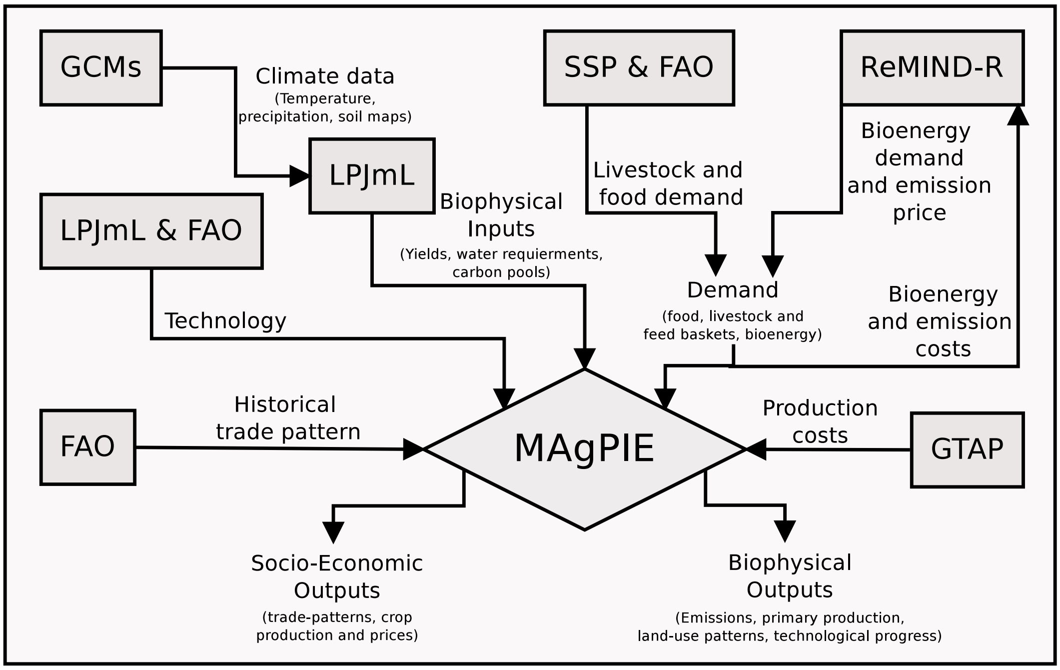

Figure 3.2 – MAgPIE model description.

information about bioenergy costs and prices as well as total GHG emissions back to the energy model. The demand for material and waste is growing proportional with food demand. The demand for seed is a fixed share of total crop production.

The GTAP database (version 4) is used to define the region-specific production costs for crops and livestock products (McDougall et al. 1998). Carbon pools and crop yields are supplied by LPJmL on a grid cell level. LPJmL simulates the outputs under current climate conditions given by the GCM. Also, water availability and requirements per crop are given by the LPJmL model (Bondeau et al. 2007). Historical trade patterns are given by FAO (FAOSTAT 2012). MAgPIE simulates the trade of crops and livestock products between regions endogenously, constrained by minimum self-sufficiency ratios for each region. There is the option to liberalize the trading market by a certain share in the model. This amount of crops is produced by the region with the lowest costs (Schmitz et al. 2012).

To reach higher production levels, MAgPIE either expands cropland or increases the yield through investments in technology (Popp et al. 2011). The model works in 10-year time steps (using 1995 as a baseline). It uses the respectively previous time step for the current optimization (Bodirsky et al. 2012a). For all provided future data MAgPIE runs with the revision number 6727 are used.

3.1.3 Future scenarios

Scenarios show a possible development of the future. They are used to better understand complex interactions in a future world. The scenarios for the used future projections in MAgPIE are based on the storylines of the SSPs. The SSPs are long-term future emission pathways developed by the IPCC and the successor of the SRES. They project the impacts of climate change to human and social systems which are affected by the reaction of earth systems. Due to the large uncertainty concerning the potential of the world society to mitigate climate change and to adapt to climate change impacts, different scenarios are created. Depending on various mitigation and adaptation potentials, the SSP scenarios are generated and numbered from 1 to 5 (O'Neill et al. 2012, Chateau 2012, Edenhofer et al. 2010b). The climate signal still varies in the single scenarios with different policy strategies depending on the aims to reduce GHG emissions. The following schema (Figure 3.3) shows the arrangement of the five pathways. For the further analysis the middle of the road scenario

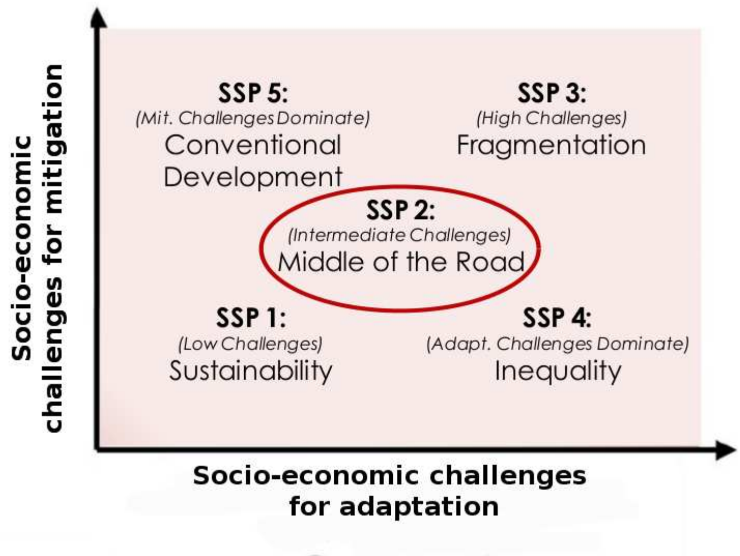

Figure 3.3 – Spanning of the different SSP scenarios, the red circle marks the used pathway, adapted from (O'Neill et al. 2012).

(SSP2) is used for two different climate goals - a SSP2 baseline scenario and a reduction scenario with a maximum of 450 ppm carbon stored in the atmosphere, called SSP2 mitigation scenario. The two scenarios are used to estimate the differences due to bioenergy production.

Bioenergy demand and GHG emission costs are included from projections of the EMF, which are based on a similar parametrization than SSP2 (EMF 2013). For the SSP2 baseline scenario only bioenergy demand is included, while in the SSP2 mitigation scenario dynamic costs for emissions are used to achieve the climate goals. The bioenergy demand is included as a fixed share for each MAgPIE region.

In SSP2, a world is depicted in which future dynamics follow historical trends with non-serious changes in behaviors. Population, the gross domestic product (GDP, which is more than 250 trillion US$PPP2005/yr in 2055) and food demand are on a medium level in comparison to other scenarios, whereby the growth in low-income countries is higher than in high-income countries. The use of fossil fuels for producing energy only declines slowly. Free trade is allowed on a small scale. There is no rapid convergence between low- and high-income countries in income-levels as well as in cooperative policy action. Only some low-income countries make good progress; others are left behind. There are still people without sufficient access to clear water, food and medical care in 2050, nor do many have access to energy. The main cause for this is a low education level. Millennium climate-goals are not achieved because there is only little access to reduce GHG emissions and protect forests as well as ecosystems. (Chateau 2012, Edenhofer et al. 2010b)

The following table (Tab. 3.2) shows the used data for the two different scenarios in 2055 and 2105 as well as the data for the starting point in 1995 (or 2005 for CO_2 emissions).

	1995	2005	2055		2105	
			SSP2 Baseline	**SSP2 Mitigation**	**SSP2 Baseline**	**SSP2 Mitigation**
Cropland [Mio ha]	1416		1524	1810	1742	2159
Population [Mio]	5545		9029		9314	
Crop demand [Mio t]	2827		6499	16949	15999	33981
Food demand [Mio t]	1728		3170	3170	3576	3576
Feed demand [Mio t]	680		2068	2062	2213	2541
Bioenergy demand [Mio t]	42		518	10863	9290	26757
Other demand [Mio t]	374		743	853	918	1107
CO_2 emissions [Mio t CO_2e]		2762	1804	6981	3760	3003
CH_4 emissions [Mio t CO_2e]	2844		6973	6610	7082	6344
N_2O emissions [Mio t CO_2e]	1758		3835	5191	5174	7267

Table 3.2 – Scenario data for the timesteps 2055 and 2105 and the starting point in 1995 (for CO_2 the starting point is 2005)

3.2 Decomposition method

3.2.1 Analyzing land use changes

First Decomposition: By defining the most important drivers of cropland changes to population, per capita demand and technology (e.g. Section 2.2), the following Kaya-like identity to decompose global cropland area in respect of the different drivers is created

$$A = P \cdot \frac{D}{P} \cdot \frac{A}{D} = p \cdot d \cdot i\,. \tag{3.3}$$

A signifies the area of cropland in million hectares, P the population in million and D the crop demand in million tons of dry matter (including food, feed crops for livestock, bioenergy, seeds, material and others). The different decomposition factors are named to p - population, d - per capita demand and i - area intensity. This identity is similar to the frequently discussed Kaya-Identity for carbon emission (Steckel et al. 2011, Raupach and Marland 2007, Albrecht et al. 2002).

To decompose cropland area on a regional scale, the demand and the production of crops have different values. Trade has an additional role and the equation extends to

$$A = P \cdot \frac{D}{P} \cdot \frac{Pr}{D} \cdot \frac{A}{Pr} = p \cdot d \cdot t \cdot i\,. \tag{3.4}$$

Pr signifies the production of all crops in million tons of dry matter and t describes the decomposition factor of trade effects. A multiplicative connection and an independence of the individual factors is assumed.

Mathematical evaluation: To convert the influences of the different factors to land use change ΔA, a decomposition with Laspeyers method (Sun and Ang 2000) is implemented. Area change can be expressed as a joint contribution of the different effects (t stands for the actual time step, so $t + 1$ represents the value for one time step into the future)

$$\Delta A = A_{t+1} - A_t = \sum_j j_a = p_a + d_a + t_a + i_a\,. \tag{3.5}$$

The single effects j_a of the different drivers (where j denotes the four drivers: population, per capita demand, trade and area intensity) are calculated in a prospective view (Sun and

Ang 2000, Sun 1998, Ang and Pandiyan 1997). The calculation shown is exemplified for the first driver, population

$$\begin{aligned} p_a = \Delta p \Big\{ &(d \times t \times i) + \\ &\frac{1}{2}(\Delta d \times t \times i + d \times \Delta t \times i + d \times t \times \Delta i) + \\ &\frac{1}{3}(\Delta d \times \Delta t \times i + \Delta d \times t \times \Delta i + d \times \Delta t \times \Delta i) + \\ &\frac{1}{4}(\Delta d \times \Delta t \times \Delta i) \Big\} . \end{aligned} \tag{3.6}$$

For all the other drivers, the correlation is in the same way.

For the global analysis the trade factor t is 1 because demand and production on a global scale are the same.

Second Decomposition: To give a special focus on the effect of bioenergy production, as one of the different demand categories for land use changes in comparison to the others, a further division of the per capita demand d into the different sectors is used. Therefore, the main sectors are identified to vegetable food demand, animal based food demand (calculated in raw crop need for livestock production, pasture is not included), bioenergy crop demand and other demands (including material, seed and others). The per capita demand d thereby can be written as

$$d = \frac{D_{\text{food}} + D_{\text{feed}} + D_{\text{bio}} + D_{\text{other}}}{P} . \tag{3.7}$$

Therein, D_{food} corresponds to the food demand, D_{feed} to the feed demand for livestock production, D_{bio} to the crop demand to produce first and second generation bioenergy and D_{other} to all other crop demands. All these values are given in million tons of dry matter.

Mathematical evaluation: To quantify the different demand categories (food, feed, bioenergy and other) in mathematical terms first, the following relation (Steckel et al. 2011) for the share of per capita demand of cropland changes d_a is identified

$$d_a = R \times \Delta d . \tag{3.8}$$

R represents the residual, which includes the influence of the other three factors (population, trade and area intensity) on the per capita demand

$$\begin{aligned} R = \big\{ &(p \times t \times i) + \frac{1}{2}(\Delta p \times t \times i + p \times \Delta t \times i + p \times t \times \Delta i) \\ &+ \frac{1}{3}(\Delta p \times \Delta \times i + \Delta p \times t \times \Delta i + p \times \Delta t \times \Delta i) \\ &+ \frac{1}{4}(\Delta p \times \Delta t \times \Delta i) \big\} \, . \end{aligned} \tag{3.9}$$

The change in per capita demand Δd can be divided into a summation over the different crop demand sectors (in this case k stands for the different sectors - food, feed, bioenergy and others)

$$\Delta d = (d_{t+1} - d_t) = \sum_k \Delta d_k = \sum_k (d_{t+1} - d_t)_k \, . \tag{3.10}$$

With $P_t = P_{t+1} - \Delta P$ and $D_{t+1} = D_t + \sum_k \Delta D_k$ the per capita demand d_{t+1} for the time step $t+1$ can be written as

$$\begin{aligned} d_{t+1} = \frac{D_{t+1}}{P_{t+1}} = \frac{D_t + \sum_k \Delta D_k}{P_{t+1}} &= d_t \frac{P_t}{P_{t+1}} + \frac{\sum_k \Delta D_k}{P_{t+1}} \\ &= d_t \frac{P_{t+1} - \Delta P}{P_{t+1}} + \frac{\sum_k \Delta D_k}{P_{t+1}} \\ &= d_t + \frac{1}{P_{t+1}} \sum_k (\Delta D_k - d_{k,t} \Delta P) \, . \end{aligned} \tag{3.11}$$

Therewith the variation from the per capita demand Δd can be described as

$$\Delta d = \frac{1}{P_{t+1}} \sum_k (\Delta D_k - d_k \, \Delta P) \, . \tag{3.12}$$

The area variation resulting of per capita demand changes d_a can be written as

$$d_a = R \times \Delta d = \frac{R}{P_{t+1}} \sum_k (\Delta D_k - d_k \, \Delta P) \, . \tag{3.13}$$

3.2.2 Analysis of CO_2 emissions in the land use sector

It is assumed that CO_2 emissions in the agricultural sector depend directly on the changes of area ΔA, but not on the used area itself, and on the carbon which is stored per hectare, named carbon content $c = \frac{CO_2}{\Delta A}$ (Van Der Werf et al. 2009, Lal 2003, Paustian et al. 2000). The following identity, which expresses carbon dioxide emissions CO_2 as a product of the drivers, is developed to analyze CO_2 emissions

$$CO_2 = \Delta A \cdot \frac{CO_2}{\Delta A} \,. \tag{3.14}$$

CO_2 emissions are given in million tons CO_2 equivalents (CO_2e) and land use changes ΔA in million hectares.

Mathematical evaluation: As seen for land use changes, also here Laspeyers method to calculate the influences of the various drivers of emissions is used. The drivers can be summed up to describe changes in CO_2 emissions

$$\Delta CO_2 = \Delta A_{CO_2} + c_{CO_2} \,. \tag{3.15}$$

Because of the fact that there are only two drivers, the calculation of the amount of each driver is simplified to

$$\Delta A_{CO_2} = \Delta(\Delta A) \times c - \frac{1}{2}\,\Delta(\Delta A) \times \Delta c \tag{3.16}$$

$$c_{CO_2} = \Delta c \times \Delta A - \frac{1}{2}\Delta c \times \Delta(\Delta A) \,. \tag{3.17}$$

The changes in the single parameters are always shown in a prospective manner, so that the future amount is subtracted from the amount of the actual time step.

The area variation in turn depends on all of the drivers described in Section 3.2.1.

3.2.3 Analysis of CH_4 emissions in agriculture

It is assumed that methane emissions from agricultural production come from two major sources. They are correlated directly with the crop production (especially rice cultivation) and accrue from livestock production (DeFries and Rosenzweig 2010). The quantification of the different drivers (population, per capita demand and technology improvements as well as the different demand categories) is done in a two step procedure.

First Decomposition: In the first step of the analysis, the CH_4 emissions arising from crop production as well as those arising from livestock management are calculated simultaneously. Values for livestock demand are given in million tons of dry matter. A similar identity as for cropland changes is set up. Thereby, methane emissions CH_4 are the product of the different drivers: population p, per capita demand d and emission factor $e = \frac{CH_4}{D}$

$$CH_4 = P \cdot \frac{D}{P} \cdot \frac{CH_4}{D} = p \cdot d \cdot e\,. \tag{3.18}$$

Emissions are calculated in million tons CO_2e in order to take global warming potentials into account, whereby CH_4 emissions must be multiplied by 25 (Ramaswamy et al. 2007). In the regional analysis one more coefficient $t = \frac{Pr}{D}$, which characterizes trade effects as the quotient of crop production Pr and crop demand D, is included

$$CH_4 = P \cdot \frac{D}{P} \cdot \frac{Pr}{D} \cdot \frac{CH_4}{Pr} = p \cdot d \cdot t \cdot e\,. \tag{3.19}$$

Mathematical evaluation: The mathematical calculations are the same as described in Section 3.2.1 using the Laspeyers method. The changes in CH_4 emissions can be written as

$$\Delta CH_4 = p_{CH_4} + d_{CH_4} + t_{CH_4} + e_{CH_4}\,. \tag{3.20}$$

Each effect is calculated as shown here exemplified for population

$$\begin{aligned} p_{CH_4} = &\Delta p \Big\{ (d \times t \times e) + \\ &\frac{1}{2}(\Delta d \times t \times e + d \times \Delta t \times e + d \times t \times \Delta e) + \\ &\frac{1}{3}(\Delta d \times \Delta t \times e + \Delta d \times t \times \Delta e + d \times \Delta t \times \Delta e) + \\ &\frac{1}{4}(\Delta d \times \Delta t \times \Delta e) \Big\}\,. \end{aligned} \tag{3.21}$$

After this decomposition, all values are given in respect to CH_4 emissions and emissions arising in crop and livestock production can be summed up to analyze the total change of CH_4 emissions ΔCH_4^{tot} in the second step

$$\Delta CH_4^{\text{tot}} = \Delta CH_4^{\text{crops}} + \Delta CH_4^{\text{ls}}\,. \tag{3.22}$$

$\Delta CH_4^{\text{crops}}$ represents influences from crop production on variations in CH_4 emissions for the different categories (population, per capita demand and emission factor) and $\Delta CH_4^{\mathrm{ls}}$ denotes the same for livestock management.

Second Decomposition: To divide the per capita demand d into the different categories an influence of crop production as well as livestock management is assumed. The effect of livestock management on per capita demand is already calculated in the first decomposition. The emissions due to the different categories of crop demand must be divided in a second decomposition. The division is implemented into food, feed, bioenergy and other demands, as in the previous analysis for cropland. Therefore, the calculations are similar to those in Section 3.2.1

$$d_{CH_4} = R \times \Delta d\,. \tag{3.23}$$

R describes residues and Δd quantifies the influences of the different crop categories (food, feed, bio and others).

Finally, the influences of livestock management is added to the influences of the different crop demand sectors and scaled to total emissions resulting from per capita demand d_{CH_4}.

3.2.4 Analysis of N_2O emission in agriculture

It is assumed that nitrous oxide emissions are mostly affected by crop production due to fertilizer use and livestock management (Mosier et al. 1998). Since the drivers are the same as these found for methane emissions the calculations are performed in a similar way. The basic approach is represented as

$$N_2O = P \cdot \frac{D}{P} \cdot \frac{N_2O}{D} = p \cdot d \cdot e \tag{3.24}$$

or as

$$N_2O = P \cdot \frac{D}{P} \cdot \frac{Pr}{D} \cdot \frac{N_2O}{Pr} = p \cdot d \cdot t \cdot e \tag{3.25}$$

with trade effects for the regional analysis. Thereby N_2O represents the nitrous oxide emissions, which are given in million tons CO_2e. This requires a multiplication by 298 and takes global warming potentials into account (Ramaswamy et al. 2007).

Mathematical evaluation: The quantification of these drivers is implemented as seen for CH_4 emissions. The resulting equations are

$$\Delta N_2O = p_{N_2O} + d_{N_2O} + t_{N_2O} + e_{N_2O}, \tag{3.26}$$

$$\begin{aligned} p_{N_2O} = \Delta p \Big\{ & (d \times t \times e) + \\ & \frac{1}{2}(\Delta d \times t \times e + d \times \Delta t \times e + d \times t \times \Delta e) + \\ & \frac{1}{3}(\Delta d \times \Delta t \times e + \Delta d \times t \times \Delta e + d \times \Delta t \times \Delta e) + \\ & \frac{1}{4}(\Delta d \times \Delta t \times \Delta e) \Big\} \,. \end{aligned} \tag{3.27}$$

The further splitting is calculated as well for N_2O emissions with

$$d_{N_2O} = R \times \Delta d \,. \tag{3.28}$$

3.2.5 Numerical calculations

All calculations are made with a R-based programming tool (R 2013, Dietrich et al. 2013). For historical analyzes yearly data as 5-year running means is used, while the data for future projections is given in 10-year time steps.

4 Results

4.1 Land use changes

This section presents the results of the analysis regarding changes in cropland. First, an overview of the last decades (1961 - 2005) is given in a historical analysis (see Figure 4.1). The results for future scenarios are depicted in Figure 4.2 on a global and in Figure 4.3 to Figure 4.6 on a regional scale. Values for yearly average growth rates are summarized in Table 4.1.

4.1.1 Historical development

In a global analysis, it can be observed that the influence on cropland expansion between 1961 and 2005 mostly occurred because of population growth and per capita demand, while increases in yields lowered these impacts (Fig. 4.1). Cropland area grew by about 9% during this time period (on average by 2 million hectares per year, see Tab. 4.1). The influence of population was nearly four times higher than the influence due to per capita demand in this past 44 years. Technological improvements in form of yield increases reduced cropland by more than 27 million hectares per year (see Tab. 4.1).

4.1.2 Future projections for the SSP2 baseline scenario

In the next decades (until 2045), global (GLO) cropland expands constantly in the SSP2 baseline scenario. Throughout the century, it increases by about 23% (approximately 330 million hectares). The influence of per capita demand is about three times higher than it has been in the past (about 17 million hectares per year) and the driving force for cropland expansion in this future scenario. It is most notable in the second half of the century. Population, in contrast, decreases its impact on cropland changes, as the yearly growth rate has

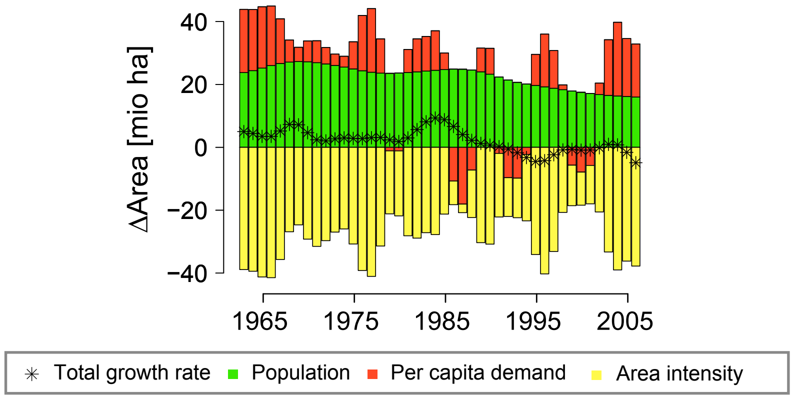

Figure 4.1 – Decomposition of yearly growth rates between 1961 and 2005 of global cropland (black stars). Bars indicate contributions from changes in population (green), per capita demand (red) and area intensity (yellow); see Equation 3.3.

about a third of the impact in comparison to per capita demand (see Tab. 4.1). Technological improvements can reduce the influences of a rising per capita demand and population growth (see Fig. 4.2 a). Compared to the past, average changes due to area intensity are slightly smaller, but they still reduce cropland by a higher amount than per capita demand increases it.

In the SSP2 baseline scenario per capita demand is not only driven by vegetable food and feed demand but also by the strong influence of crop demand for bioenergy (see Fig. 4.2 a). In the first half of the century, livestock feed demand still has a considerable contribution to cropland increases, but from the middle of the century on (when second generation bioenergy is one of the major energy sources), bioenergy mainly drives cropland expansion. Over the observed time period bioenergy is responsible for more than 50% of land use changes. Vegetable food demand and others do not contribute to a significant pressure on land expansion.

Different world regions show diverging trends (see Figure 4.3). Cropland expands the most in Sub-Saharan Africa (AFR) and Latin America (LAM) but for different reasons. The influence of population is particularly high in developing regions (e.g. AFR). In these regions, the effect of per capita demand on cropland is comparably smaller, even if per capita demand is already low today in contrast to other regions. Most regions reflect the major influence of per capita demand observed in the global analysis. This value largely depends on crop demand for bioenergy, especially in Centrally Planned Asia including China (CPA), LAM and North America (NAM) (see Tab. 4.1 and Fig. 4.4). In AFR and the Former Soviet Union (FSU) bioenergy is an important driver in the last decade of the century as well. On average over the whole century, bioenergy increases cropland by more than 1 million hectares in AFR, CPA, LAM and NAM. Besides bioenergy, feed demand for livestock production is an

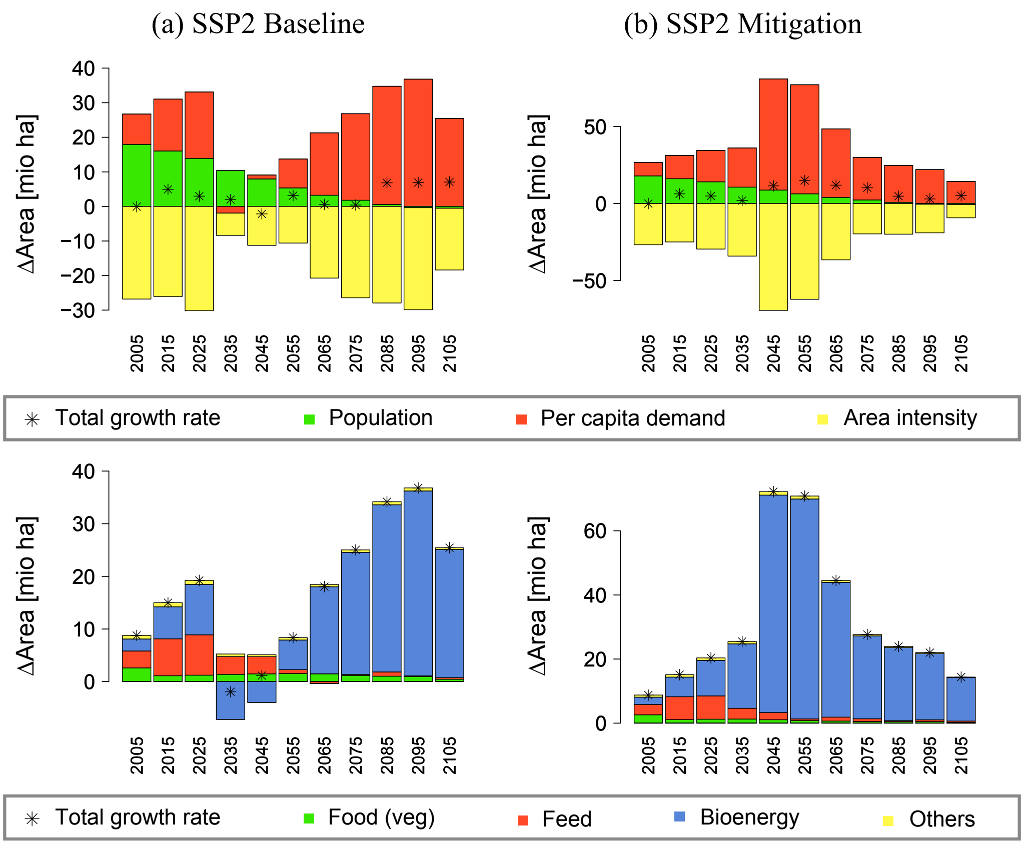

Figure 4.2 – Decomposition of yearly growth rates between 2005 and 2105 of global cropland (black stars, above) and the influence of per capita demand on cropland (black stars, below) for the different scenarios (SSP2 baseline (a) and SSP2 mitigation (b)). Bars indicate contributions from changes in population (green), per capita demand (red) and area intensity (yellow) in the first decomposition (above) and changes in food (green), feed (red), bioenergy (blue) and others (yellow) in the further decomposition (below); see Eq. 3.3 and Eq. 3.7.

important driver for per capita demand in AFR, CPA and South Asia including India (SAS). A declining population in CPA (resulting mainly from Chinese policy) reduces the pressure on cropland. In other developed countries (e.g. Europe including Turkey (EUR), FSU and Pacific OECD including Japan, Australia, New Zealand (PAO)) a decrease in population leads to less cropland expansion, but with a smaller influence. Trade has a varying impact on cropland. AFR and FSU are the largest exporters and LAM and NAM are the largest importers (see Tab. 4.1). But there are no continuous trends. Technological improvements reduce the pressure on cropland in all regions in the entire century. The reductions are higher in developing countries than in developed countries.

The reduction of cropland, with a lower bioenergy crop cultivation, in Latin and North America between 2035 and 2055 are further discussed in Chapter 5.

4.1.3 Future projections for the SSP2 mitigation scenario

In total, cropland expands even more in the SSP2 mitigation scenario then in the SSP2 baseline scenario during the current century. In numbers it increases by about 50% of 1995's value, approximately 750 million hectares, until 2105. After a decline in net yearly cropland expansion rates in the next decades (until 2035), the establishment of second generation biofuels in the energy system increases the expansion rate in the middle of the century again (see Fig. 4.2 b). In comparison to the SSP2 baseline scenario, population shows a similar influence on cropland changes, while the influence of per capita demand nearly doubles (see Tab. 4.1). Technological improvements are higher than in the baseline case and similar to the range of historical yearly values. They can lessen the influence on rising per capita demand, but they cannot compensate the pressure of both population and demand.

In the SSP2 mitigation scenario, bioenergy is responsible for nearly 90% of future pressure on cropland due to per capita demand (see Fig. 4.2 b) and for about 70% of the changes respectively to all drivers. Feed demand has an influence of less than 10% on the per capita demand. This influence occurs mainly during the first decades of the century. Influences from vegetable food demand and others are even smaller.

At the regional level, the high global pressure due to per capita demand is reflected in AFR, CPA, FSU, LAM, NAM and SAS (see Tab. 4.1 and Fig. 4.5). Per capita demand is mostly driven by bioenergy in all these regions (see Fig. 4.6). However, in AFR the influence due to population growth is in the same range as per capita demand. Feed demand for livestock production also influences cropland, mostly in AFR, CPA, FSU, and SAS, with a yearly growth rate of about 0.5 to 1.1 million hectares. In contrast to this value, bioenergy drives cropland by more than 7 million hectares per year in LAM and by more than 25 million hectares in the global yearly average. Trade effects are comparably smaller than other drivers, while CPA exports and FSU and NAM import the most. Decreasing area intensities reduce cropland use in all world regions.

	Region	Area	Population	Per capita demand	Trade	Area intensity	Food (veg)	Feed	Bio	Other
History	GLO	2,09	22,61	6,55		-27,07				
SSP2 Baseline	GLO	2,96	6,93	17,28		-21,25	1,31	2,39	13,04	0,53
	AFR	1,13	3,12	2,21	0,17	-4,37	0,31	0,46	1,30	0,14
	CPA	0,47	-0,63	3,39	0,10	-2,39	0,06	0,83	2,41	0,08
	EUR	-0,23	-0,05	0,35	-0,05	-0,48	0,22	-0,06	0,16	0,03
	FSU	-0,50	-0,30	0,51	0,41	-1,13	0,17	-0,12	0,43	0,02
	LAM	1,71	0,64	4,56	-0,24	-3,25	0,11	0,40	3,97	0,08
	MEA	-0,05	0,35	0,09	-0,04	-0,45	0,00	0,09	0,00	0,01
	NAM	0,29	1,01	1,36	-0,14	-1,94	0,27	-0,58	1,59	0,08
	PAO	-0,16	-0,12	0,15	0,04	-0,23	0,10	0,05	0,00	0,01
	PAS	0,06	0,21	0,30	-0,20	-0,24	0,08	0,18	0,00	0,03
	SAS	0,23	0,94	1,13	-0,41	-1,43	0,34	0,70	0,00	0,09
SSP2 Mitigation	GLO	6,76	7,25	31,38		-31,88	0,96	2,46	27,35	0,61
	AFR	1,24	3,14	3,29	-0,01	-5,18	0,27	0,51	2,38	0,12
	CPA	1,06	-0,93	4,68	0,16	-2,85	0,02	0,66	3,91	0,09
	EUR	-0,01	-0,08	0,57	-0,18	-0,31	0,22	0,08	0,24	0,03
	FSU	0,09	-0,35	1,78	-0,50	-0,83	0,15	1,15	0,38	0,09
	LAM	3,42	0,64	8,43	-0,15	-5,50	0,08	0,26	7,98	0,11
	MEA	-0,02	0,35	0,09	-0,05	-0,41	0,00	0,08	0,00	0,01
	NAM	0,77	1,06	5,24	-0,69	-4,84	0,23	-0,31	5,22	0,10
	PAO	-0,15	-0,12	0,26	0,04	-0,32	0,09	0,05	0,10	0,02
	PAS	-0,05	0,21	0,70	-0,08	-0,89	0,07	0,20	0,39	0,03
	SAS	0,40	0,97	2,12	-0,15	-2,53	0,34	0,56	1,10	0,11

Table 4.1 – Yearly growth rates of cropland changes in million hectares per year for past and future scenarios.

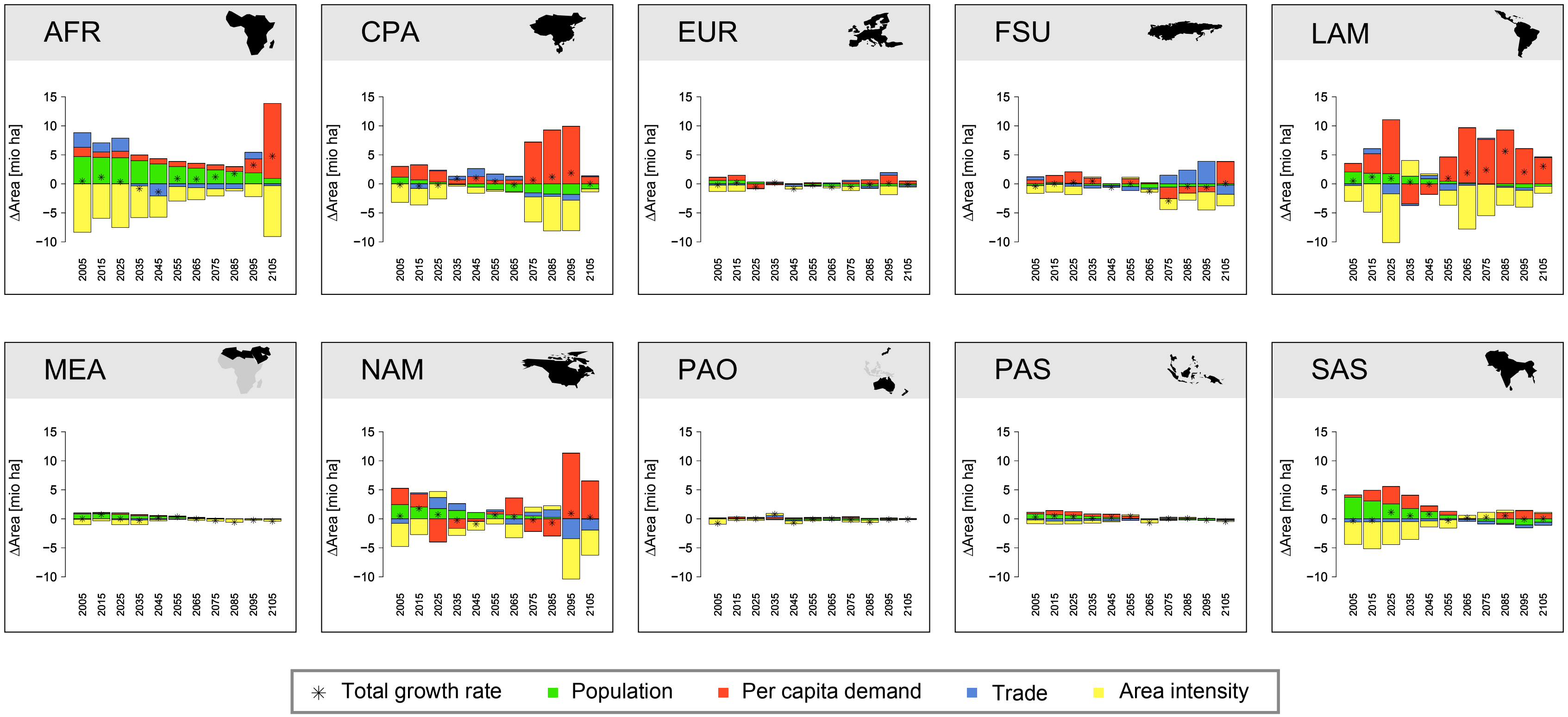

Figure 4.3 – Decomposition of yearly growth rates for cropland (black stars) in the SSP2 baseline scenario for all 10 world regions. Bars indicate contributions from changes in population (green), per capita demand (red), trade (blue) and area intensity (yellow); see Eq. 3.4.

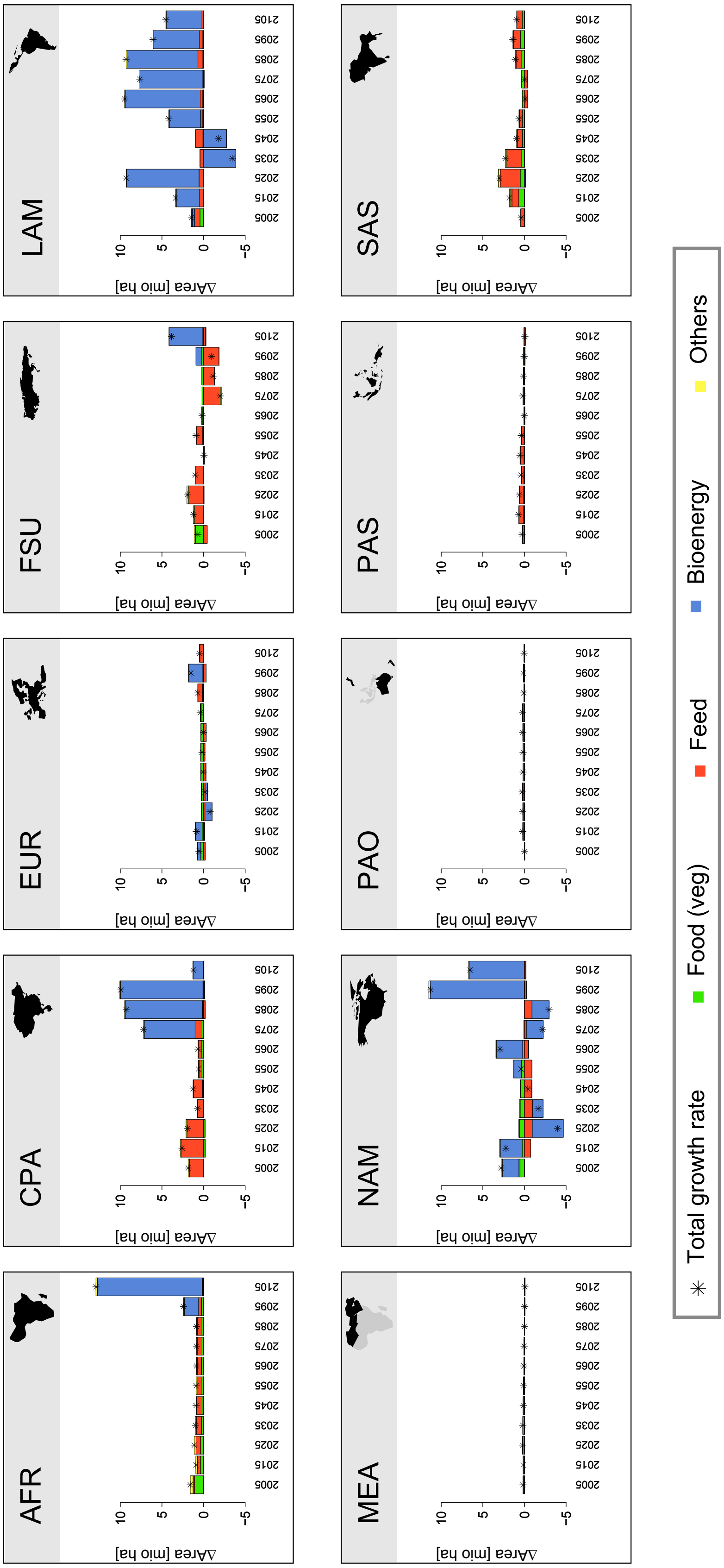

Figure 4.4 – Decomposition of yearly growth rates of cropland demand (black stars) in the SSP2 baseline scenario for all 10 world regions. Bars indicate contributions from changes in food (green), feed (red), bioenergy (blue) and other (yellow) demand; see Eq. 3.7.

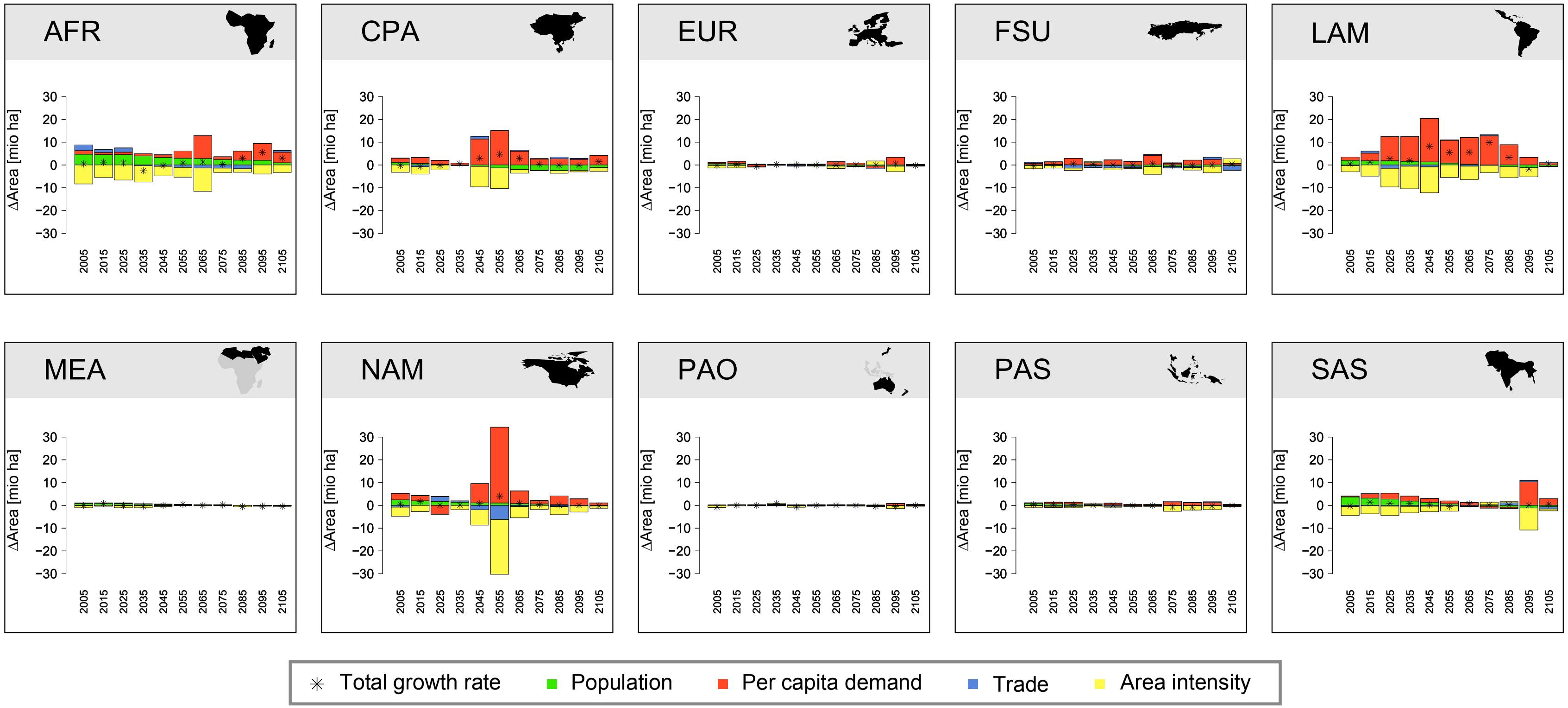

Figure 4.5 – Decomposition of yearly growth rates for cropland (black stars) in the SSP2 mitigation scenario for all 10 world regions. Bars indicate contributions from changes in population (green), per capita demand (red), trade (blue) and area intensity (yellow); see Eq. 3.4.

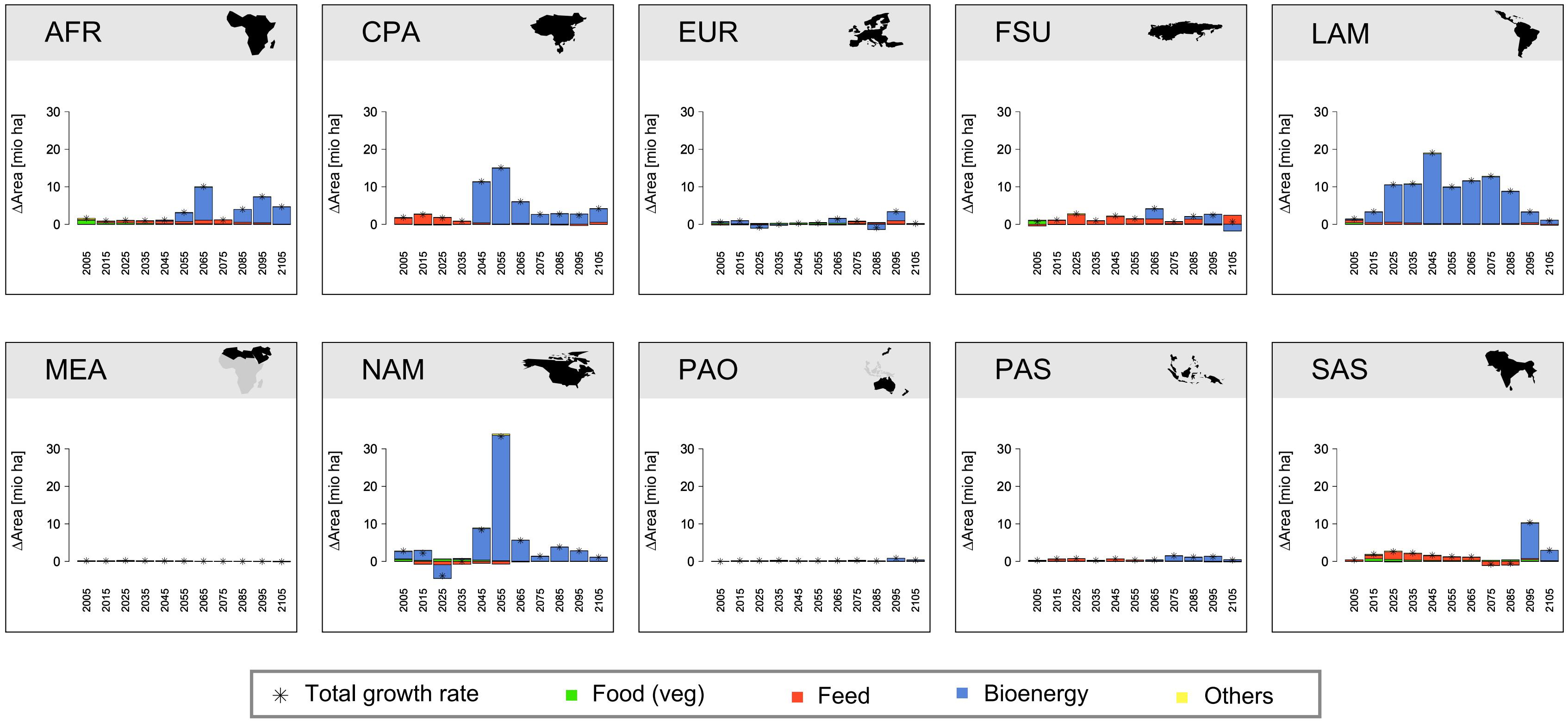

Figure 4.6 – Decomposition of yearly growth rates of cropland resulting from per capita demand (black stars) in the SSP2 mitigation scenario for all 10 world regions. Bars indicate contributions from changes in food (green), feed (red), bioenergy (blue) and other (yellow) demand; see Eq. 3.7.

4.2 Changes of GHG emissions in agriculture

The following section presents the results for GHG emission changes in agriculture. Negative influences on emission changes are not equal to negative emissions but stand for lower emissions than in the previous timestep. The historical development is shown in Figure 4.7, 4.9 and 4.11 and global future projections are depicted in Figure 4.8, 4.10 and 4.12. Average yearly growth rates for the single drivers are summarized in Table 4.2, 4.3 and 4.4. The figures for the regional analysis are presented in the annex (see Fig. A.1 to Fig. A.10).

4.2.1 Carbon dioxide emissions

Historical development: CO_2 emissions were influenced by both area variation and carbon content of the converted land, with a fluctuating effect in the last 35 years (see Fig. 4.7). When large areas were converted into cropland, carbon contents were declining in comparison to the previous time step and the other way around. In total, CO_2 emissions rose by 14%. Due to land use changes the emissions increased on average by about 34 million tons CO_2e per year.

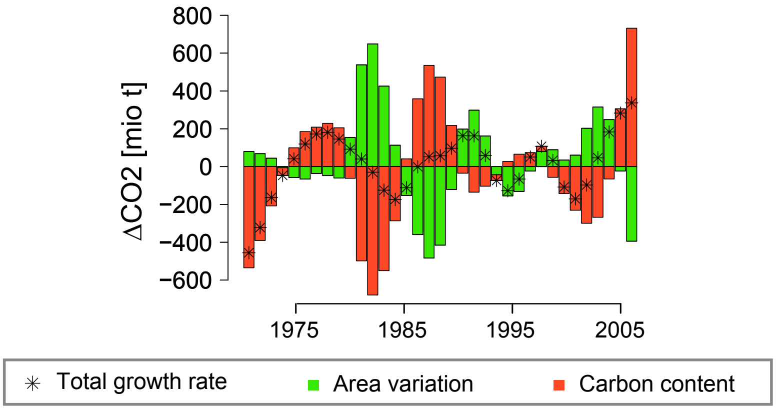

Figure 4.7 – Decomposition of yearly growth rates between 1970 and 2005 of global CO_2 emissions (black stars). Bars indicate contributions from changes in area variation (green) and carbon content (red); see Eq. 3.14.

SSP2 baseline scenario: In this century, CO_2 emissions increase due to the conversion of lands with a high carbon content into cropland with a lower potential to store carbon (see Fig. 4.8 a). The influence to increase emissions of area variation itself is higher than the influence of carbon contents. Throughout the century CO_2 emissions increase on average by about 10 million tons CO_2e per year (see Tab. 4.2). Area variations are responsible for the rise of emissions while the conversion of land with low carbon contents can slightly reduce the amount.

On a regional level, land use changes that lead to CO_2 emissions mainly appear in AFR and LAM while emissions can be significantly reduced in CPA, NAM, PAO and Pacific (or South east) Asia (PAS) (see Fig. A.1, annex). In LAM the increase is mostly driven by the area variation itself. In AFR, both carbon content and area variation, lead to higher CO_2 emissions. Strong varying influences in CO_2 emissions can be seen particularly in developing regions with potentials for new cropland.

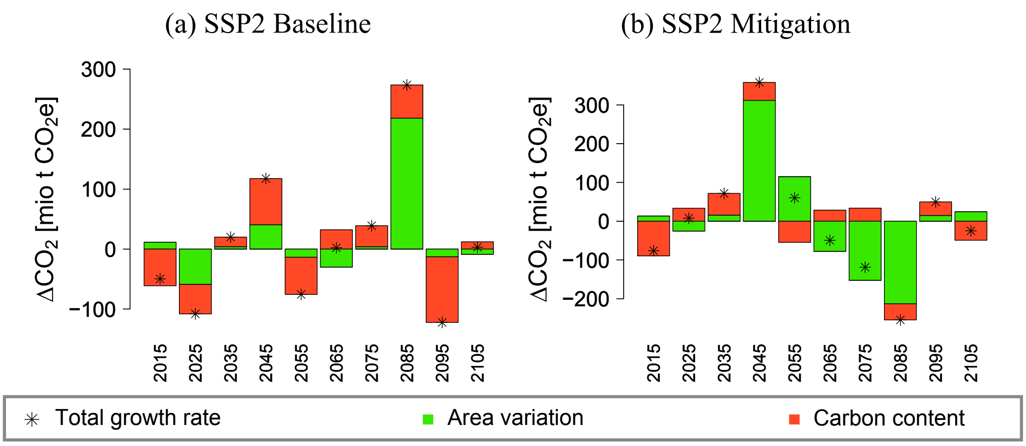

Figure 4.8 – Decomposition of yearly growth rates between 2005 and 2105 of global CO_2 emissions (black stars) for the different scenarios (SSP2 baseline (a) and SSP2 mitigation (b)). Bars indicate contributions from changes in area variation (green) and carbon content (red); see Eq. 3.14.

SSP2 mitigation scenario: In the SSP2 mitigation scenario CO_2 emissions increase less than they do in the baseline case (by about 2.4 million tons CO_2e per year, see Tab. 4.2). Area variations influence CO_2 emissions by a smaller amount than in the SSP2 baseline scenario on average over the entire observed time period (see Fig. 4.8 b). Carbon contents influence CO_2 emissions in varying ways. On average, a slight decline of emissions due to smaller carbon contents can be observed (see Tab. 4.2).

Regional trends are most notable in AFR, CPA, LAM and NAM over the entire observed time period (see Tab. 4.2 and Fig. A.2, annex). Highest reduction can be observed in LAM and PAO. For detailed information of all regions see Table 4.2 and the figures in the annex concerning CO_2 (Fig. A.1 and A.2).

	Region	CO_2 emission	Area variation	Carbon content
History	GLO	10,22	33,95	-23,74
SSP2 Baseline	GLO	9,97	15,35	-5,38
	AFR	15,29	9,86	5,43
	CPA	-3,75	3,86	-7,61
	EUR	-0,23	-0,25	0,02
	FSU	-0,17	0,14	-0,30
	LAM	4,48	9,92	-5,44
	MEA	0,09	0,00	0,08
	NAM	-1,25	0,64	-1,89
	PAO	-3,86	-3,85	-0,01
	PAS	-1,36	-0,23	-1,13
	SAS	0,75	-1,90	2,65
SSP2 Mitigation	GLO	2,41	2,56	-0,16
	AFR	10,22	2,28	7,95
	CPA	2,04	-1,48	3,52
	EUR	-0,23	-0,27	0,04
	FSU	-0,22	0,24	-0,46
	LAM	-3,24	-8,85	5,60
	MEA	0,13	0,08	0,05
	NAM	-2,36	-1,54	-0,82
	PAO	-3,90	-4,10	0,20
	PAS	-1,36	-1,53	0,17
	SAS	1,33	-0,45	1,77

Table 4.2 – Yearly growth rates of changes in CO_2 emissions in million tons CO_2e per year for past and future scenarios.

4.2.2 Methane emissions

Historical development: History shows that population was the most important driver of CH_4 emissions between 1970 and 2005 (see Fig. 4.9). Since 1970, CH_4 emissions in agriculture increased by about 14%. The influence of per capita demand was only about one fourth of the impact of population (see Tab. 4.3). Improvements in technology reduced the CH_4 released to the atmosphere by about 60 million tons CO_2e per year.

SSP2 baseline scenario: Net CH_4 emissions increase until the end of the century by about 150% in the SSP2 baseline scenario. Population and per capita demand are the major drivers of CH_4 emission changes and responsible for more or less the same part of the

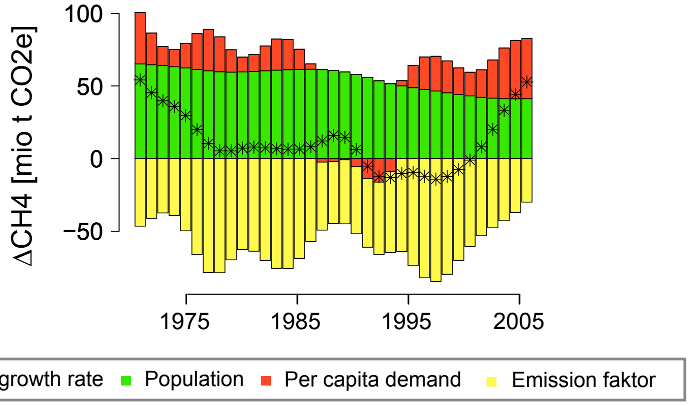

Figure 4.9 – Decomposition of yearly growth rates between 1970 and 2005 of global CH_4 emissions (black stars). Bars indicate contributions from changes in population (green), per capita demand (red) and emission factor (yellow); see Eq. 3.18.

increase (each for more than 20 million tons CO_2e per year, see Tab. 4.3 and Fig. 4.10 a). Technological improvements reduce the emissions by only about 10 million tons CO_2e per year globally. In comparison to past trends where technological improvements reduced CH_4 emissions by about 60 million tons CO_2e per year, this value is low. The influence due to population becomes smaller over time, but the total net yearly rise of emission quadruples to about 40 million tons CO_2e per year in comparison to the past.

Emissions resulting from per capita demand are mostly driven by livestock production (see Fig. 4.10 a). The yearly average growth rate is about 20 million tons CO_2e (see Tab. 4.3), but until the middle of the century the pressure is more eminent than in the second half. Over the whole century, livestock production contributes to about 40% of the CH_4 emission increases. It also seems as bioenergy drives CH_4 emissions. But at this point a shortcoming in methodology is reached which is discussed in Section 5.

In particular, CH_4 emissions increase largely in AFR, LAM and SAS (see Fig. A.3, annex). This effect is mostly driven by population and per capita demand. In CPA trade and per capita demand are responsible for the increase of emissions while the declining population leads to less emissions. In LAM trade also affects emission rises by a significant amount. Emission increases due to per capita demand is generally driven by livestock production (see Fig. A.4, annex). Food, feed and other demands have almost no influence on CH_4 emissions. For the detailed information of all regions see Table 4.3 and the figures in the annex (Fig. A.3 and Fig. A.4).

SSP2 mitigation scenario: The development of CH_4 emissions is similar in the mitigation case and the SSP2 baseline scenario (see Fig. 4.10 b). The value of total increase

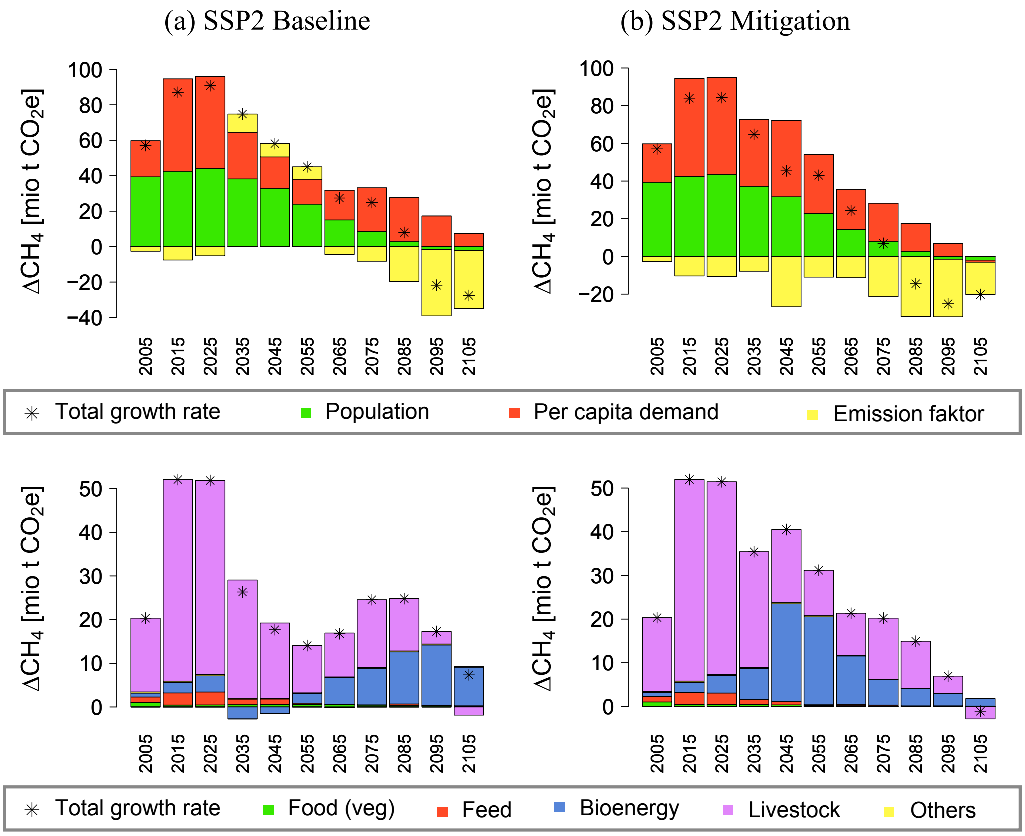

Figure 4.10 – Decomposition of yearly growth rates between 2005 and 2105 of global CH_4 emissions (black stars, above) and the influences of per capita demand (black stars, below) on CH_4 for the different scenarios (SSP2 baseline (a) and SSP2 mitigation (b)). Bars indicate contributions from changes in population (green), per capita demand (red) and emission factor (yellow) in the first decomposition (above) and changes in food (green), feed (red), bioenergy (blue) and others (yellow) as well as livestock management (magenta) in the further decomposition (below); see Eq. 3.18 and 3.7.

is about 123% over the course of the century. Per capita demand has a slightly higher influence and technology improves. More than twice the emissions can be reduced with decreasing emission factors in comparison to the SSP2 baseline scenario (see Tab. 4.3). There are no large differences to the baseline scenario on a regional scale (see Fig. A.5 and A.6, annex).

	Region	CH_4	Population	Per capita demand	Trade	Emission factor	Food (veg)	Feed	Bio	Other	Livestock
History	GLO	11,59	54,89	14,95		-58,25					
SSP2	GLO	38,52	22,15	24,83		-8,46	0,50	0,93	4,90	0,20	18,29
Baseline	AFR	20,72	18,93	17,31	-3,85	-11,67	0,04	0,06	0,21	0,02	16,99
	CPA	1,10	-2,71	3,28	2,63	-2,10	0,03	0,68	1,16	0,06	1,34
	EUR	-0,74	-0,12	-1,24	1,08	-0,46	0,01	0,00	0,00	0,00	-1,25
	FSU	0,62	-0,55	0,52	0,38	0,27	0,07	-0,30	0,55	-0,01	0,21
	LAM	5,63	3,15	3,34	2,64	-3,50	0,03	0,11	0,98	0,02	2,21
	MEA	1,09	0,69	0,97	-0,44	-0,13	0,00	0,01	0,00	0,00	0,96
	NAM	-0,29	0,97	-0,98	-0,10	-0,19	0,02	-0,04	0,12	0,01	-1,08
	PAO	-0,13	-0,47	-0,34	1,08	-0,40	0,02	0,01	0,00	0,00	-0,38
	PAS	0,48	0,76	2,31	-1,00	-1,60	0,17	0,40	0,00	0,07	1,68
	SAS	10,03	3,99	16,47	1,84	-12,26	0,20	0,45	0,00	0,06	15,75
SSP2	GLO	31,82	21,68	26,65		-16,51	0,31	0,85	7,46	0,19	17,83
Mitigation	AFR	20,41	18,88	17,29	-3,86	-11,90	0,03	0,05	0,20	0,01	16,99
	CPA	-1,44	-1,62	4,73	1,86	-6,41	0,00	0,57	1,55	0,05	2,56
	EUR	1,68	-0,32	-1,48	1,27	2,21	0,01	0,00	0,01	0,00	-1,50
	FSU	1,61	-0,61	-0,25	1,02	1,45	0,01	0,04	0,01	0,01	-0,31
	LAM	0,39	3,33	4,50	0,30	-7,74	0,02	0,06	1,84	0,03	2,57
	MEA	1,09	0,69	0,97	-0,44	-0,13	0,00	0,01	0,00	0,00	0,96
	NAM	0,74	0,98	-0,78	0,08	0,46	0,01	-0,02	0,29	0,01	-1,08
	PAO	-0,14	-0,55	-0,35	1,24	-0,48	0,02	0,01	0,02	0,00	-0,41
	PAS	-0,08	0,78	2,98	-0,69	-3,15	0,14	0,44	0,54	0,06	1,80
	SAS	7,55	3,89	15,35	1,47	-13,17	0,19	0,40	0,35	0,06	14,35

Table 4.3 – Yearly growth rates of changes in CH_4 emissions in million tons CO_2e per year for past and future scenarios.

4.2.3 Nitrous oxide emissions

Historical development: In the last decades (1970-2005), total nitrous oxide emissions increased by about 70%. The most important driver for this increase was population (see Fig. 4.11). Yearly growth rates of N_2O emissions due to per capita demand could be compensated by technological improvements (see Tab. 4.4). In comparison to the reduction of CH_4 emissions with lowering emission factors, N_2O emissions were only reduced by about 8 million tons CO_2e per year over the whole time period, which is less than the seventh part of the reduction of CH_4 emissions.

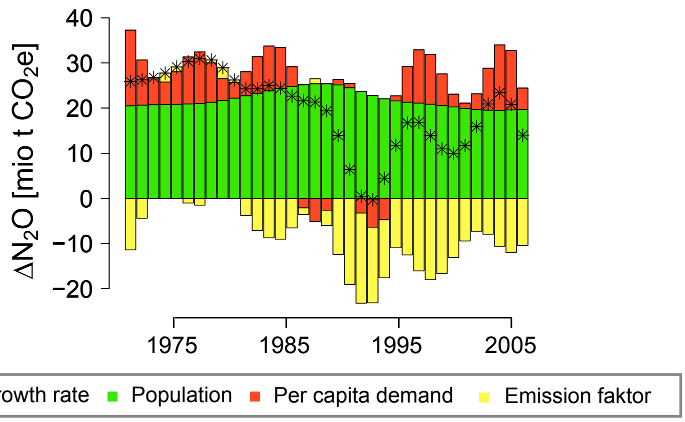

Figure 4.11 – Decomposition of yearly growth rates between 1970 and 2005 of global N_2O emissions (black stars). Bars indicate contributions from changes in population (green), per capita demand (red) and emission factor (yellow); see Eq. 3.24.

SSP2 baseline scenario: In the SSP2 baseline scenario N_2O emissions follow historical rising trends but with a higher average yearly growth rate of about 30 million tons CO_2e (see Fig. 4.12 a, Tab. 4.4). Over the entire century, they nearly triple in respect to the 1995's value. The influence of per capita demand exceeds the influence of population. Technological improvements have a little slighter the reduction effect than they had in the last four decades.

In the first half of the century, the major driver for emissions resulting from per capita demand is livestock management and feed demand, while in the second half it is bioenergy production (see Fig. 4.12 a). In average, bioenergy is responsible for nearly 40% of the changes in N_2O emissions. Food and other demands have comparably smaller influences.

The highest regional trends of N_2O emission rise occur in AFR, CPA, LAM and SAS. In AFR and SAS this rise is mostly driven by population and per capita demand, which in turn consists mainly of livestock demand (see Fig. A.7 and A.8, annex). In AFR bioenergy also affects N_2O emissions in the end of the century. In CPA livestock production has a fluctuating influence on emission, while it forces emissions to rise in LAM but with a smaller rate than bioenergy. In CPA and LAM bioenergy is the main driver, especially from the middle of the century on. The effect of bioenergy also appears in EUR and NAM from 2050 on, but with a smaller impact. The detailed information for all regions can be found in Table 4.4 and the figures in the annex (Fig. A.7 and A.8).

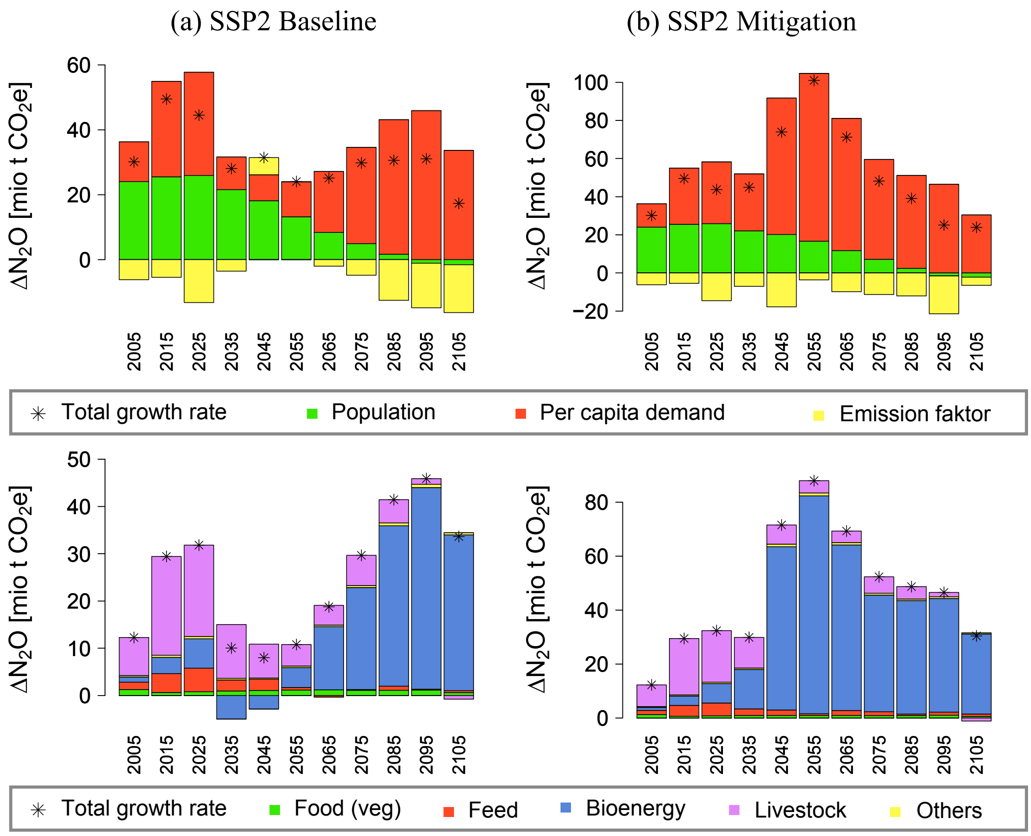

Figure 4.12 – Decomposition of yearly growth rates between 2005 and 2105 of global N_2O emissions (black stars, above) and the influences of per capita demand (black stars, below) on N_2O for the different scenarios (SSP2 baseline (a) and SSP2 mitigation (b)). Bars indicate contributions from changes in population (green), per capita demand (red) and emissions factor (yellow) in the first decomposition (above) and changes in food (green), feed (red), bioenergy (blue) and others (yellow) as well as livestock management (magenta) in the further decomposition (below); see Eq. 3.24 and Eq. 3.7.

SSP2 mitigation scenario: In the mitigation case N_2O emission rise is about 60% larger than in the SSP2 baseline scenario and more than a double in respect to the 1995's value (see Fig. 4.12 b, Tab. 4.4). This increase is mainly influenced by per capita demand, which is driven by livestock production including feed demand in the beginning of the century and by bioenergy over the entire period of time. The influence of bioenergy is in particular high in the second half of the century. Technological improvements are too small to compensate the influences of both population and per capita demand.

Bioenergy influences N_2O emissions significantly higher than livestock production (including feed demand) does (see Tab. 4.4). In the SSP2 baseline scenario this influence is only a third of the influence as in the SSP2 mitigation scenario. In the SSP2 mitigation scenario bioenergy contributes to nearly 60% of total changes of N_2O emissions.

Regional trends for a high increase of N_2O emissions appear particularly in AFR, CPA, LAM, NAM, and SAS (see Fig. A.9 and A.10, annex). Also on a regional level they are mostly driven by bioenergy with the exception of AFR and SAS, where livestock production has a significant influence as well. In CPA the influence of animal based food production takes place only in the coming three decades. The detailed information for all regions can be found in Table 4.4 and in the figures in the annex concerning N_2O (Fig. A.9 and A.10).

	Region	N_2O	Population	Per capita demand	Trade	Emission factor	Food (veg)	Feed	Bio	Other	Livestock
History	GLO	19,36	21,94	5,32		-7,90					
SSP2	GLO	31,05	12,79	24,71		-6,44	1,00	1,55	13,79	0,43	7,93
Baseline	AFR	12,85	9,87	9,88	-1,81	-5,09	0,20	0,42	2,19	0,11	6,96
	CPA	4,84	-2,81	8,66	1,34	-2,36	0,14	1,35	6,10	0,16	0,91
	EUR	-0,24	-0,10	-0,10	0,33	-0,36	0,20	-0,05	0,15	0,03	-0,44
	FSU	-0,33	-0,20	0,24	0,08	-0,45	0,04	-0,04	0,14	0,00	0,09
	LAM	8,62	1,80	6,99	1,19	-1,37	0,10	0,36	5,28	0,08	1,16
	MEA	0,67	0,60	0,60	-0,26	-0,26	0,00	0,06	0,00	0,00	0,54
	NAM	0,62	1,20	0,61	-0,14	-1,06	0,19	-0,43	1,36	0,06	-0,56
	PAO	-0,08	-0,26	-0,10	0,51	-0,23	0,05	0,03	0,00	0,01	-0,18
	PAS	0,29	0,30	1,13	-0,41	-0,72	0,04	0,10	0,00	0,02	0,97
	SAS	3,80	1,16	4,96	0,72	-3,04	0,11	0,25	0,00	0,03	4,56
SSP2	GLO	50,08	13,81	46,44		-10,17	0,90	1,92	35,11	0,64	7,87
Mitigation	AFR	14,49	10,24	11,73	-2,15	-5,33	0,15	0,56	3,97	0,09	6,96
	CPA	7,25	-4,25	13,76	1,56	-3,83	0,09	1,11	11,07	0,21	1,29
	EUR	0,42	-0,16	-0,03	0,27	0,33	0,19	0,06	0,20	0,03	-0,51
	FSU	0,33	-0,27	0,34	0,19	0,07	0,03	0,27	0,08	0,02	-0,06
	LAM	18,30	1,67	18,44	0,36	-2,17	0,10	0,31	16,44	0,21	1,39
	MEA	0,67	0,60	0,60	-0,27	-0,26	0,00	0,06	0,00	0,00	0,54
	NAM	4,05	1,41	5,23	-0,74	-1,84	0,17	-0,24	5,80	0,09	-0,59
	PAO	-0,05	-0,30	-0,03	0,61	-0,32	0,05	0,03	0,07	0,01	-0,19
	PAS	0,79	0,26	1,55	-0,19	-0,83	0,04	0,09	0,39	0,02	1,00
	SAS	3,83	1,12	5,13	0,57	-2,99	0,13	0,20	0,55	0,04	4,21

Table 4.4 – Yearly growth rates of changes in N_2O emissions in million tons CO_2e per year for past and future scenarios.

5 Discussion

The following chapter points out which shortcomings may appear due to the model and the decomposition method. It further examines the results and compares them to other projections. Finally, the development of the drivers and how they influence the impacts in the past and in the future is analyzed.

5.1 Shortcomings in data and methodology

Shortcomings occur due to limitations and quality of data and during the technical realization of the analysis in methodology.

5.1.1 Limitation in data quality

Databases for land use improved in the past years (Fritz et al. 2013, Erb et al. 2007), but estimated potentials for cropland have high uncertainties (Schmitz et al. 2013). Schmitz et al. (2013) compared the land use outputs of different models under SSP scenarios. They observed that outputs from MAgPIE are in the same range as values from other land use models. The projection that 40% of suitable cropland will be in use by 2050 of Bruinsma (2009) stays in line with the observed 38% to 45% share of suitable cropland-use by 2055 in this present analysis.

The used data for GDP and population are taken out of SSP projections, which are considered to be the most recent (Kriegler et al. 2012), and determine the demand in MAgPIE. To compare the used demand data to other projections the output variable bioenergy is used exemplary because of its large influence on agricultural impacts. Bioenergy crop demand increases to 0.5 Gt dry matter in the SSP2 baseline scenario and to 10.8 Gt dry matter in the SSP2 mitigation scenario by 2055. These crops produce about 150 EJ of bioenergy in the baseline case, more than 500 EJ in the mitigation case, and use about 7% or 64% of cropland.

Other studies projected bioenergy potentials in 2050 to 100 - 1000 EJ/yr (Popp et al. 2010). The study of Beringer et al. (2011) found similar potentials for “sustainable” bioenergy in a “food first” scenario (130 - 270 EJ in 2050) than one observes in this study in the baseline case. The high bioenergy production in the mitigation case in contrast could be an indication for the production of energy instead of food.

The used values of GHG emissions are provided by MAgPIE. In the past decades, agriculture and land use changes have been responsible for more than 30% of total anthropogenic greenhouse gas emissions (EPA 2006). With a continuation of the current trends and no additional action to mitigate Flynn and Smith (2010) estimated the yearly emissions in agriculture to rise by about 35% until 2030. The data used for the present analysis projects a similar increase in GHG emissions of about 30% due to agriculture by 2035.

Additional aspects for data quality occur because data is not in the needed format or information is not included in MAgPIE. The crop production for the ten world regions was not given for single categories and assumptions were made (see Eq. 3.1 and 3.2). However, only for about 15% of crops these assumptions need to be implemented. Consequently, the potential uncertainties do not have a predominant influence on the results. Further, MAgPIE does not include all possible mitigation activities to reduce CH_4 and N_2O emissions. This leads to an underestimation of technological improvements and is notable if past development is compared to future projections. Particularly for CH_4 emissions, technological improvements are much higher in history than in future projections.

5.1.2 Limitations of methodology

The method allows a consistent comparison of land resources and release of GHG emissions for the different demand sectors in agricultural production. It can be used on a regional and global scale and quantifies per capita demand as well as other drivers for agriculture. However, the decomposition does not allow interactions between the single parameters so all drivers are treated as if they were independent. In reality this is not the case, e.g. technological improvement depends on per capita demand and population (especially due to the scarcity of land and the need to reduce emissions), whilst population is also coupled to per capita demand.

To estimate the scale of the error made by the assumption of independent factors, two runs of the model with different population inputs are used. One with the projected SSP2 changes and one with a constant population (value in 1995). The two data sets of cropland changes and demand are used with the constant population value in 1995 for the decomposition (see Fig. 5.1). At the beginning of the century, when population has a significant influence, cropland seems to expand more due to per capita demand (see Figure 5.1 a) than without population influences (see Figure 5.1 b). Influences on cropland due to per capita demand and area intensity vary in the two figures. It can be seen clearly that the drivers are not independent in the model. Otherwise the two figures would exactly look the same. However, major trends are the same in both figures and can easily be shown using this method. Further advantages of the method are that it decomposes single factors consistently and quantifies the drivers of a certain impact. This makes it easy to compare the influences without starting additional runs and calculation efforts.

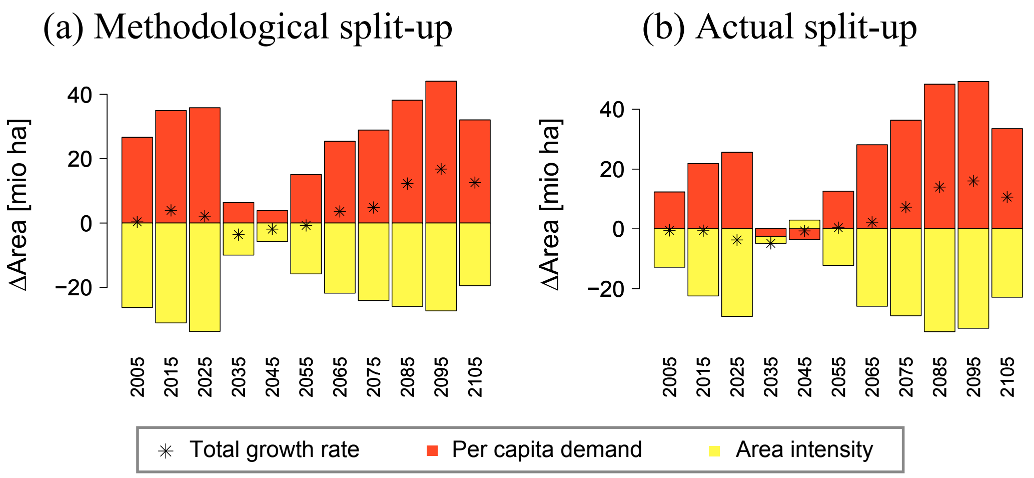

Figure 5.1 – Decomposition of yearly growth rates between 2005 and 2105 of global cropland (black dots) without changes in population. Bars indicate contributions from changes in per capita demand (red) and area intensity (yellow) in the SSP2 baseline scenario run with population influences (a) and without population influences (b) to aggregate data for cropland and crop demand.

An additional shortcoming in methodology appears during the further decomposition of per capita demand, when the total demand value is divided into the different categories (food, feed, bioenergy and others). It is assumed that the total value is equally split into the share of each category depending on the amount of cropland or released emissions for the certain category. Sometimes, this is not realistic because crops especially used in one category may release more emissions or use more cropland than others, which are mainly used in another category. The problem is that information about the crop type is not included in the decomposition analysis. This might result in an incorrect assignment. Among others, this problem is notable in the analysis by further decomposing the per capita demand concerning CH_4 emissions. Most of these emissions result from either livestock management or rice cultivation. Emissions from livestock management are treated separately, but for rice cultivation they are divided into demand categories, even though rice is mostly used for food (neither for feed nor for bioenergy). The influence of feed or bioenergy crop demand in Figure 5.2 (a) actually comes from food demand (see Fig 5.2 b). An analysis of single crop types would be better to understand certain effects of emissions in the different demand categories.

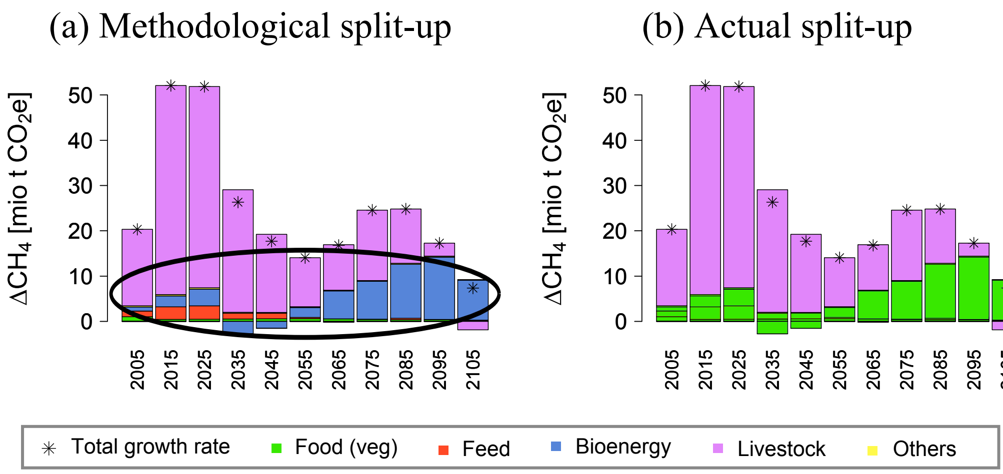

Figure 5.2 – Decomposition of global per capita demand concerning CH_4 emissions. The blue and red bars which indicate the influences of bioenergy and feed demand (a, marked area) should actually come from food demand (green, b).

5.1.3 Scopes of the analysis

By using the decomposition method, some limitations occur for an entire analysis of agricultural impacts on the environment. For example, the land used for agricultural production does not only include arable land, which contains land under annual cultivation but also permanent cropland and pasture. To discuss the influences on land and emissions in agriculture completely, examinations of these land types should be included. Moreover, only land use changes and GHG emissions as environmental impacts of agricultural production are regarded. The analysis of changes in biodiversity, soil, water and air contamination could complete the study. In addition, crop demand declared as fooder is not included because of the high uncertainties of historical data for this value.

Furthermore, a detailed analysis of area intensity and emission factors would be interesting to better understand the influences of certain technological improvements as they are the key element to higher future production quantities. However, assumptions have to be made first to better model these parameters with computer based projections. Moreover, this study does not quantify the effect of technological improvements on CO_2 emissions. At this point, a further examination of the connection between yield improvements and possible reductions of CO_2 emissions due to less land use changes is needed.

5.2 Key findings and Comparison

The impact of certain drivers of agricultural production is changing over time. The major drivers in the future are discussed in this section and changes to past trends are taken up. Four key findings are specified.

5.2.1 Bioenergy - The new key driver for land use changes, CO_2 and N_2O emissions

This analysis points out that bioenergy drives land use changes, N_2O emissions and CO_2 emissions due to land use changes as the major force. Compared to the other drivers, bioenergy plays a major role. The influence of bioenergy is larger with additional mitigation activities than in the SSP2 baseline scenario for cropland and N_2O emissions. For CO_2 emissions it is lower in the SSP2 mitigation scenario than in the baseline case, because less cropland expands into lands with large carbon contents.

Even if the replacement of fossil fuels by bioenergy increases GHG emissions in agriculture, it has a reducing effect on net GHG emissions in the entire system. The carbon emitted to the atmosphere by using biofuels was earlier taken out of it during the cultivation of the energy crops (Cherubini and Strø mman 2011). In combination with CCS, bioenergy has the potential to produce even negative GHG emissions (Popp et al. 2011).

All over the century, bioenergy is responsible for about 50% of land use changes in the SSP2 baseline and for about 70% in the SSP2 mitigation scenario. Regarding this analysis, bioenergy is responsible for about 20% of cropland increase until 2025 in both scenarios. Similar values are found in scenarios presented by Gallagher (2008), where bioenergy production was estimated to increase the demand for cropland by about 17% to 44% until 2020, depending on the amount of cultivated crops for bioenergy production and on technological improvements. The drastic decrease of cropland due to bioenergy in LAM and NAM between 2035 and 2055 in the SSP2 baseline scenario result from a drop in first generation bioenergy. The establishment and production of second generation bioenergy begins only in the middle of the century, because efficiency and technological improvements are necessary for an economically worthwhile production. In the SSP2 mitigation scenario research starts earlier and the economically profitable production of second generation bioenergy already begins in the coming decades (see Fig. 4.2).

If cropland is expanded into forests and ecosystems with high carbon contents, it results in large amounts of CO_2 emissions (Popp et al. 2011, Wirsenius et al. 2010). Because bioenergy is the main driver for cropland expansion it is mainly responsible for CO_2 emissions from land use changes.

Furthermore, bioenergy accounts for about 37% of the increase of N_2O emissions until the end of the century in the SSP2 baseline and for about 58% of the changes in the SSP2 mitigation scenarios. N_2O emissions arise because of the greater use of fertilizers to produce bioenergy crops. First generation biocrops need high amounts of fertilizer and the resulting emissions might be higher than the avoided emissions due to the use of fossil fuels (Crutzen and Mosier 2008). Second generation bioenergy (with lower fertilizer needs) has a higher potential to reduce global warming (Crutzen and Mosier 2008). By contrast, this study observes particularly large influences of bioenergy on N_2O emissions when second generation bioenergy is used (see Fig. 4.12). This might result from the significant increase of bioenergy production quantity when second generation techniques are used and the replacing of fossil fuels (energy sector) with bioenergy (agricultural sector). Fertilizer use in particular mounts N_2O emissions in the developing countries in Africa, Latin America and Asia due to the extended production of bioenergy (Reay et al. 2012). For CPA and LAM this trend is reflected in this analysis (see Fig. A.7 and A.9, annex).

Over the whole observed time period bioenergy forces N_2O emissions with a higher amount in the SSP2 mitigation (35 million tons per year) than in the SSP2 baseline scenario (14 million tons per year). One can conclude that mitigation policy is an additional force for GHG emissions in the agricultural sector. However, with the replacing of fossil fuels with bioenergy a shift of emissions from the energy to the agricultural sector takes place and a reduction of total anthropogenic GHG emissions can be achieved.

5.2.2 Livestock - The major source for CH_4 emissions in agriculture

Currently the livestock sector (especially cattle breeding) is responsible for about 80% of agricultural GHG emissions, mainly CH_4 and N_2O (O'Mara 2011). This study observes that this sector is the main driver for CH_4 emissions in the future as well (it is responsible for about 40% of the changes in CH_4 emissions in both scenarios). Due to animal-based food production CH_4 emissions increase by about 23 million tons per year in the SSP2 baseline and by more than 25 million tons per year in the SSP2 mitigation scenario.

O'Mara (2011) projected a growth in CH_4 emissions of 30% between 2000 and 2020 due to livestock production. This study, in comparison, shows that livestock production causes a similar amount of about 45% CH_4 emissions until 2025 in both observed scenarios.

O'Mara (2011) further identified Europe, North America and the Former Soviet Union as the most efficient livestock producers and developing countries (in Africa, Latin America and Asia) as the least efficient livestock producers. These trends are projected into the future in this study (see Fig. A.3 and A.5, annex). Livestock demand mainly drives emissions in AFR, CPA, LAM, PAS and SAS. In particular AFR and SAS are identified as regions being highly influenced by livestock production in a long term view. These are the regions with the lowest current demand of animal products and an increase of their production is foreseeable and can be seen as an equalization with consumption patterns in other regions.

5.2.3 Technological change - The main reducer for the impacts of agricultural production

As observed in this analysis, technological improvements can largely reduce cropland expansion, but the improvements to reduce CH_4 and N_2O emissions with technical support are lower. This may result from the implication of only few options to decline emission factors in the model. In contrast to the forcing drivers, area intensities and emissions factors are the main reducers of cropland expansion and increasing GHG emissions.

Area intensity reduces cropland expansion in the past as well as in the future. Depending on the level of intensification Tilman and Balzer (2011) estimated 0.2 to 1 billion hectares land clearing due to technological improvements by 2050. In comparison, this study indicates that by 2055 1.2 billion hectares in the SSP2 baseline and 3.5 billion hectares in the SSP2 mitigation scenario less are converted into cropland because of decreasing area intensities. Rudel et al. (2009) projected a smaller effort of intensified production. It spares only about 230 million hectares cropland until 2050 in his analysis. The data used for this study projects not only intensification but also better management and resource usage, which might lead to higher values than other observations.

Without improvements in area intensity and the same pressure due to demand, about 2300 million hectares more cropland would be used by the end of the century in the SSP2 baseline scenario. This stands for about one sixth of total ice-free land and would reach the amount of suitable cropland if the actual land in agricultural use is added (another 1400 million hectares) (Lambin and Meyfroidt 2011). One perceives regional differences concerning technological improvements. Past improvement rates in Africa are lower than in other regions, so the potential to increase yields is large (Pretty et al. 2011). This study points out that in comparison to other regions, improvements due to technological changes in AFR can lower agricultural impacts drastically. Besides the positive effect of land savings due to land intensification, it can also cause environmental impacts as GHG emissions (Tscharntke et al. 2012).

Technological improvements, such as the optimization of the use of resources (e.g. fertilizer) and better management, can reduce CH_4 and N_2O emissions (Reay et al. 2012, Zhuang and Melack 2009). The reduction potential largely depends on knowledge and research (Harvey and Pilgrim 2011, Smith et al. 2010). The observed reduction effort for emissions is smaller than for land use changes (15 million tons CO_2e in the SSP2 baseline and 26 million tons CO_2e in the SSP2 mitigation scenario). In the past, higher yields could avoid emissions of up to 590 Gt CO_2e between 1961 and 2005 (Burney et al. 2010). This past value is much higher, but it also includes emission reductions due to land use changes which are not quantified in this work.

Reay et al. (2012) discovered large reduction potential of N_2O emissions by optimizing fertilizer efficiency and cutting down over-consumption in China and India, among others. This trend is reflected in this analysis in the next decades in CPA and SAS (see Fig. A.7 and A.9). Another point of view states that the use of more nitrogen fertilizer has potential to increase yields in Africa and give the possibility for more productivity and thus the decrease of hunger (Pretty et al. 2011).

Various studies observed that the shift to diets with less meat consumption has a high potential to reduce emissions as well (Taheripour et al. 2013, Reay et al. 2012, O'Mara 2011, Popp et al. 2010). Popp et al. (2010) estimated a reduction potential of 70% of CH_4 emissions by 2055 in a "low meat" consumption scenario. They concluded that the reduction of non-CO_2 emissions due to technological improvements takes even less effort then the reduction of meat consumption. The analysis of a scenario with different livestock shares could validate these statements and numbers in detail.

5.2.4 Lower influence of past major drivers

In this analysis, the growth rates for cropland changes due to the single drivers are in line with historical developments but they change over time. Figure 5.3 shows historical calculations and values for the SSP2 baseline projections. Population decreases constantly and declines in growing rates. Per capita demand forces cropland mainly in the end of the century. Technology reduces the pressure on cropland over the entire time period.

In a future world with a stagnating population, bioenergy (the biggest share of per capita demand) replaces population (Huber et al. 2013, Kastner et al. 2012) as one of the main

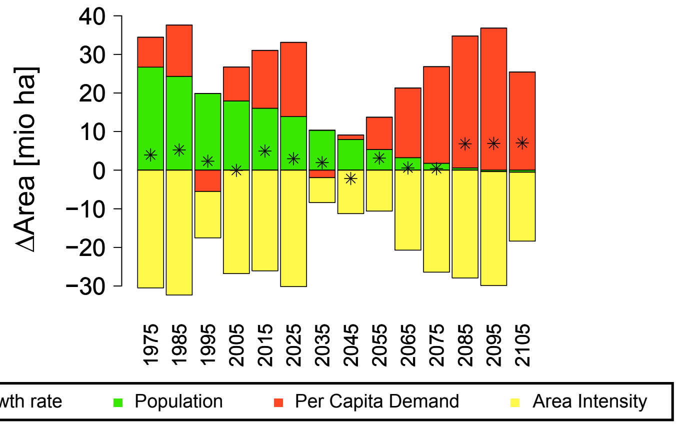

Figure 5.3 – Combination of historical and future decomposition of yearly growth rates (between 1965 and 2105) of global cropland A (black dots). Bars indicate contributions from changes in population (green), per capita demand (red) and area intensity (yellow); see Eq. 3.3.

drivers of cropland expansion and rising GHG emissions in agriculture. Gerbens-Leenes and Nonhebel (2002) pronounced a change from the past significant driver population towards a greater influence of bioenergy and diets. Population instead only has significant effects in developing countries (e.g. AFR and SAS), but also in these regions the impact slows down towards the end of the century.

In the past, it was not the bioenergy demand but dietary changes that influenced per capita demand and thus, cropland and GHG emissions. In the last decades, per capita meat production grew constantly. Currently livestock production causes about 80% of land use changes, including pasture (Stehfest et al. 2009) (this study observes only 33% cropland changes due to the rising feed demand) and is responsible for 80% of current non-CO_2 emissions (O'Mara 2011). However, yearly growth rates decreased in recent years (Taheripour et al. 2013). In the future, the change towards more meat-based diets only have a predominate effect on CH_4 emissions but not on the other impacts of agriculture.

Gibbs and Ruesch (2010) observed that already today crop demand for food, feed and bioenergy is the main driver of changes in cropland and agricultural GHG emissions. In comparison, this study shows only a contribution due to per capita demand of about one third to land use changes and increasing non-CO_2 GHG emissions in 2005. However, this share rises in the future when population decreases and bioenergy crops represent an increasing amount of crop demand.

5.3 Interpretation of the drivers and policy implication

Some drivers of agricultural production are not easy to regulate and manage. The following section describes the consequences of the drivers in the future and the problems which appear in controlling them. Further, some advise for policy implications is given.

5.3.1 Population

In the analysis, changes in population influence both cropland and emissions in a similar way. The earlier the population peaks, the earlier the influence on agricultural production drops. Depending on the underlying scenario the moment of the peak varies.

Controlling the population is not necessarily wanted and can be ethically questioned. Population is difficult to manage without forbidding the right of reproduction. Especially in the developing world, population peaks only after the middle of the current century. Programs to help women plan their pregnancies already reduce the number of births (Bongaarts and Sinding 2011). Indeed, a forced family planing program can be one “of the most consequential social experiments” (Feng et al. 2013), as it is seen in China today. “Unprecedented governmental interventions” (Feng et al. 2013) as they have existed since 1979 in China, lead to a higher male/female ratio of born children and boost abortion rates (Hesketh et al. 2005).

It has been observed that the number of births largely correlates to education levels of women (Lutz and Kc 2011). A way to control births without restricting human rights could be a better education system worldwide and more public information about contraceptive possibilities.

5.3.2 Per capita demand

The analysis shows that a rising per capita demand drives cropland and GHG emissions. Thereby, the dimension depends on the certain demand category because of their different influence on agricultural impacts.

In our globalized world a rising consumption – for agricultural products equal to crop demand in the present analysis – is important for a growing economy. At some point, however, it has to be dealt with the earth’s limits (physical land limitations, the scarcity of resources

– like water and phosphorous – and the human carrying capacity of the earth) (Smit and Bindraban 2009, Erb et al. 2007, Wallace and Gregory 2002, Cohen 1995) and anthropogenic influences on climate and biodiversity (due to agricultural systems) (Aneja et al. 2009, Henle et al. 2008, Butler et al. 2007, Liu et al. 2003). There might be a possibility for wealth without increasing consumption and to divide resources equally and fairly in the near future, to leave a functioning planet for next generations.

Because of the strong influence of bioenergy production in the future, this aspect is discussed separately in section 5.3.3. First, the focus lies on challenges and problems of per capita food demand, due to social and ethical effects, as it can fall under a limit where people in certain regions may suffer from hunger and starvation. Further, the influences of livestock product demand are discussed.

Food demand: By analyzing and discussing the per capita food demand it is always important to give a special focus on the backgrounds of an increasing or decreasing demand. For example, the slowing off in per capita food demands in Sub-Saharan Africa in the past was not because people reduced surplus demands but rather because of infeasible climate conditions or extreme weather events as well as high food prices (Schmidhuber and Tubiello 2007, Haile 2005). These circumstances can result in undernourishment in some countries, while there still exists over-consumption and a high wasting rate in others, mostly developed regions (Ajanovic 2011). In 2007, more than 900 million people suffered under malnutrition because of high food prices (Webb 2010). An increase of food consumption over a certain limit (2200 kcal/day/capita) in other regions (e.g. Europe and North America) is not necessary (Smil 2000). Reductions are desirable in order to reduce waste and decrease the consumption of products with high resource demands (mainly animal products). Especially for the reduction of waste, no individual abdication of certain products is required. Only with better management and planning of food consumption, per capita food demand could be halved in some developed regions (Smil 2000).

Human alimentation does not have to consist of the current large amount of animal products. The consumption of these can be reduced easily without driving undernourishment. Instead, it could rather help to minimize world hunger, because less resources would be used for the production of food (Bogdan et al. 2010, Smil 2000). Furthermore, an over-consumption of livestock products can boost certain health risks like cancer, obesity and heart diseases (Erb et al. 2012). For the production of livestock groceries, multiple times more resources are required than in vegetable food production and additional CH_4 and N_2O emissions are released during the production cycle (Wirsenius et al. 2010, Smil 2000). Climate policies in terms of, for example, output taxes on emission- or land-intensive crops, lead to higher prices of livestock products and can reduce the demand (especially the consumption of the resource intensive ruminant meat) (Wirsenius et al. 2011). Increasing prices for livestock products take off pressure from land and GHG emissions (Wirsenius et al. 2010), but they would refuse these high protein products for people with low income.

5.3.3 Bioenergy demand

Bioenergy, as the biggest share of per capita demand in both the SSP2 mitigation and the SSP2 baseline scenario is the dominant driver for cropland expansion and GHG emissions in the future. However, it can be an important energy source for future generations.

One of the most important environmental problems now and for the future is climate change. In the past two decades, it has been discussed more and more in global politics. Regulations and limitations for GHG emissions were determined from a group of countries – especially European countries decided ambitious emission reduction targets (Manne and Richels 1998). The use of biomass as a resource for energy started to be seen as an option to reduce emissions on one hand. On the other, it has an additional pressure on land and stands in competition to other crop-using sectors such as food production. The positive and negative consequences of bioenergy are discussed in detail.

To prevent GHG emissions that increase the global mean temperature, the use of fossil fuels to provide energy must be substituted with new solutions. Bioenergy has the potential to produce a considerable part of future energy and plays an important role in the global energy mix (Bellevrat et al. 2008, Gielen et al. 2003, Berndes et al. 2003). Especially for transportation, biofuels have a major role because they are not bound on a certain place and can be transported like fossil oil or gas. Bioenergy can be produced in a decentralized way, which gives the possibility of energy independence, especially for farmers in rural areas in developing countries. In addition to food production, it can be a new source of income and brings competition to fossil fuels.

Along with its positive impacts, bioenergy has some disadvantages. Concerning resource availability for land, water and fertilizer amongst others, the bioenergy sector competes with human food production. The production of biomass for energy provision can also lead to managed monocultures and water contamination (Field et al. 2008). It supports land degradation and the conversion of forests into croplands (Campbell et al. 2008, Goldemberg 2007). Therefore it destroys biodiversity and carbon stocks (Field et al. 2008, Gallagher 2008). Due to the advanced pressure on land and water, bioenergy production might contribute to higher food prices and support global undernourishment (Popp et al. 2011, Gallagher 2008).

For environmental reasons, it is important how biofuels are produced and which kind of land is converted to cultivate the energy crops (Fargione et al. 2008). The use of wasted biomass or plants which grew on abandoned land to produce energy might be a better possibility to prevent future GHG emissions than the use of energy crops, grown on fertile cropland (Fargione et al. 2008). The amount of resources used for the production of bioenergy always has to be on a level to secure sufficient food availability for the whole population, without high price increases for basic food products. In developing countries, bioenergy is often used for the energy consumption on a household level - cooking and heating - with a low efficiency (Mueller and Schmidhuber 2008). This resource efficiency can be heightened by using improved technologies with a better know-how.

5.3.4 Technological changes

Next to land expansion technological improvements can lead to higher production quantities. A decreasing area intensity or emission factor can be also seen as a reduction of cropland or GHG emissions. Especially in developing countries, there is a high potential to improve technology because of the current low standards (Dietrich et al. 2012).

The present study shows that in the past technological changes reduced both cropland expansion and GHG emissions. Without these improvements the world would already expand the amount of suitable land for a sustainable crop production (Huber et al. 2013). However, they do not always have only positive effects for the environment. An overuse of fertilizer and pesticides changes the soil conditions and pollutes water and air. But with good management and the minimization of possible negative influences they lead to a higher production quantity. (Tilman and Balzer 2011, Burney et al. 2010, Godfray et al. 2010b)

Regarding the rising crop demand for the future, technological improvements for agricultural cultivation are indispensable. The reduction of the pressure on land and GHG emissions depends on knowledge about smart and sustainable solutions for agricultural production and thus on financial support of research (Harvey and Pilgrim 2011, Smith et al. 2010). Akimoto et al. (2010) estimated high low-cost (or rather no-cost) potentials for the reduction of GHG emissions in agricultural production in comparison to other sectors. This study shows that in all ten world regions decreases of area intensity and emissions factor can reduce the impacts of agriculture in the future. However, it largely depends on research and dissemination whether yield increases, the optimization of fertilizer use and livestock management is able to reduce the pressure on land and GHG emissions (Smith et al. 2010). To achieve sustainable agriculture with less emissions and land use, investments as well as policy action are needed (Beddington and Asaduzzaman 2012, Cerri et al. 2010).

5.3.5 Trade

Trade can have a positive effect, as it reduces global cropland as well as costs when high efficient regions export and low efficient regions import food crops and commodities (Schmitz et al. 2012). As it is notable in the regional analysis (see Fig. 4.3, 4.5, A.3 to A.9) the amount of traded products increases until the end of the century.

Trade not only has the positive effect that all kinds of crops produced all over the world can be consumed everywhere, but it also has some negative consequences. Fuels powering engines for transportation cause additional GHG emissions (Verburg et al. 2009). Because of long distances, crops or processed agricultural products may go off and get wasted (Nordström and Vaughan 2000). Emissions resulting from transportation are not included in the analyzed data. Thus, for an entire analysis, this value should be examined as well.

6 Conclusion

Agricultural production is one key element to provide sufficient food for the growing population of the world. In the future, global agricultural output is predicted to increase not only due to rising food consumption, but also because of increasing crop demand for bioenergy production. Agriculture has damaging impacts to the environment with the destruction of biodiversity by expanding cropland and the change of climate conditions by the emission of GHGs being just some examples. Thus, the main challenge for the agricultural sector is the increase of production quantities while reducing the agricultural footprint with sustainable solutions. To implement such sustainable agricultural pathways a deep understanding of the underlying drivers such as population growth, changing consumption patterns but also potential future pressures on the agricultural system like crop production for bioenergy is strongly needed.

Therefore, in this study, the different drivers of land use changes and GHG emissions in agriculture are quantified. It appears that in the future, past drivers as population growth and changes in per capita food demand lose their major influence on agricultural production. In the observed scenarios, bioenergy becomes the greatest force for most environmental impacts such as land use changes and increasing GHG emissions. Thereby, the allocation of energy with agricultural products endangers global food security by competing with food production for available resources such as land, water and fertilizer. However, even as a competitor to food production and its large influence on the environmental impacts of agriculture, bioenergy might produce negative net GHG emissions as it is used in combination with carbon capture and storage and replaces fossil fuels. To still guarantee global food demand, enough cropland has to be available for the cultivation of food and feed crops. Besides, the quantity of allocated energy can be improved by additionally using wasted biomass as feedstock for bioenergy production.

The present analysis shows that livestock production, another driver for agriculture, causes only changes in CH_4 emissions as the major force. However, CH_4 emissions represent a non-negligible part of 50% of total emissions [CO_2e] in agriculture. Therefore, a large potential to reduce GHG emissions can be seen in shifting diets towards a consumption of less animal-based groceries without endangering global food security.

Besides the forcing drivers of agriculture (bioenergy and livestock production), in this study a decrease in emission factors and area intensities is identified as the main reducers of the pressure on land and GHG emissions. These technological improvements can be seen as a key element to achieve the expected large future production quantities. However, the different options for technological changes are not analyzed in detail and the potentials are underestimated in comparison to past observations (Burney et al. 2010). For a proceeding study, it is desirable to pay deeper attention to the role of single technological practices and management options which might reduce agricultural impacts on the environment in the coming decades.

Bibliography

Ajanovic, A. (2011). Biofuels versus food production: Does biofuels production increase food prices? *Energy*, 36(4):2070–2076.

Akimoto, K., Sano, F., Homma, T., Oda, J., Nagashima, M., and Kii, M. (2010). Estimates of GHG emission reduction potential by country, sector, and cost. *Energy Policy*, 38(7):3384–3393.

Albrecht, J., François, D., and Schoors, K. (2002). A Shapley decomposition of carbon emissions without residuals. *Energy Policy*, 30(9):727–736.

Aneja, V. P., Schlesinger, W. H., and Erisman, J. W. (2009). Effects of agriculture upon the air quality and climate: research, policy, and regulations. *Environmental science & technology*, 43(12):4234–40.

Ang, B. and Pandiyan, G. (1997). Decomposition of energy-induced CO2 emissions in manufacturing. *Energy Economics*, 19(3):363–374.

Banse, M., van Meijl, H., and Woltjer, G. (2008). The Impact of First and Second Generation Biofuels on Global Agricultural Production, Trade and Land Use. In *The 11th Annual GTAP Conference*, pages 1–14, Helsinky. Agricultural Economics Research Institute (LEI).

Beddington, J. and Asaduzzaman, M. (2012). What next for agriculture after Durban. *Science*, 335:289–290.

Bellevrat, E., Kitous, A., and Isaac, M. (2008). Bio-Energy Use and Low Stabilization Scenarios. *The Energy Journal*, 31(S1):193–222.

Beringer, T., Lucht, W., and Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, 3(4):299–312.

Berndes, G., Hoogwijk, M., and van den Broek, R. (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy*, 25(1):1–28.

Bodirsky, B. L., Popp, a., Weindl, I., Dietrich, J. P., Rolinski, S., Scheiffele, L., Schmitz, C., and Lotze-Campen, H. (2012a). Current state and future scenarios of the global agricultural nitrogen cycle. *Biogeosciences Discussions*, 9(3):2755–2821.

Bodirsky, B. L., Rolinski, S., Biewald, A., Popp, A., and Lotze-campen, H. (2012b). Global food demand scenarios for the 21st century. *submitted*.

Bogdan, A., Miresan, V., Sonea, A., Chelmu, S., Boboc, V., Surdu, I., Burlacu, R., Diaconescu, D., and Strateanu, A. (2010). Prospects for Development of Livestock Production between 2010–2100 Based on Integrated Rural Bioeconomics and Ecoeconomics. *Bulletin UASVM Animal Science and Biotechnologies*, 67(1-2):19–28.

Bondeau, A., Smith, P. C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., and Smith, B. (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, 13:679–706.

Bongaarts, J. and Sinding, S. (2011). Population policy in transition in the developing world. *Science*, 333:574–576.

Bruinsma, J. (2009). The resource outlook to 2050: By how much do land, water and crop yields need to increase by 2050? In *How to feed the World in 2050. Proceedings of a FAO Expert Meeting*, pages 24–26.

Burney, J. A., Davis, S. J., and Lobell, D. B. (2010). Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences of the United States of America*, 107(26):12052–12057.

Butler, S. J., Vickery, J. a., and Norris, K. (2007). Farmland biodiversity and the footprint of agriculture. *Science (New York, N.Y.)*, 315:381–384.

Calderini, D. F. and Slafer, G. a. (1998). Changes in yield and yield stability in wheat during the 20th century. *Field Crops Research*, 57(3):335–347.

Campbell, J. E., Lobell, D. B., Genova, R. C., and Field, C. B. (2008). The global potential of bioenergy on abandoned agriculture lands. *Environmental science & technology*, 42(15):5791–4.

Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. a., and Marland, G. (2007). Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America*, 104(47):18866–70.

Cerri, C., Bernoux, M., and Maia, S. (2010). Greenhouse gas mitigation options in Brazil for land-use change, livestock and agriculture. *Scientia Agricola*, 67(1):102–116.

Chateau, J. (2012). Working Party on Climate, Investment and Development: Long-term Economic Growth and Environmental Pressure: Reference Scenarios for Future Global Projections. Technical report, Organisation for Economic Co-operation and Development.

Cherubini, F. and Strø mman, A. H. (2011). Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresource technology*, 102(2):437–451.

Cohen, J. E. (1995). Population Growth and Earth's Human Carrying Capacity. *Science*, 269:341–346.

Cole, C. V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., and Zhao, Q. (1997). Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nurientt Cycling in Agroecosystems*, 49:221–228.

Crutzen, P. and Mosier, A. (2008). N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics*, 8:389–395.

Davis, S. C., House, J. I., Diaz-Chavez, R. a., Molnar, A., Valin, H., and Delucia, E. H. (2011). How can land-use modelling tools inform bioenergy policies? *Interface Focus*, 1(2):212–223.

DeFries, R. and Rosenzweig, C. (2010). Toward a whole-landscape approach for sustainable land use in the tropics. *Proceedings of the National Academy of Sciences of the United States of America*, 107(46):19627–19632.

Delgado, C. L., Courbois, C. B., and Rosegrant, M. W. (1998). Global food demand and the contribution of livestock as we enter the new mellennium. In *British Society of Animal Science – Kenya Agricultural Research Institute Conference entitled "Food, Lands and Livelihoods: Setting Research Agendas for Animal Science"*, number 21, pages 1–32, Nairobi, Kenya. Kenya Agricultural Research Institute.

DeVries, F. W. T. P., van Keulen, H., and Rabbinge, R. (1995). Natural resources and limits of food production in 2040. *Eco-Regional Approaches for Sustainable Land Use and Food Production*, pages 65–87.

Dietrich, J. P., Krause, M., Rolinski, S., Bodirsky, B., Schmitz, C., Mueller, S., Miodrag Stevanovic, M. B., Waha, K., Faul, F., Humpenoeder, F., and Neher, I. (2013). landuse: R-Package of the landuse group.

Dietrich, J. P., Schmitz, C., Müller, C., Fader, M., Lotze-Campen, H., and Popp, A. (2012). Measuring agricultural land-use intensity – A global analysis using a model-assisted approach. *Ecological Modelling*, 232:109–118.

Dietrich, P. J. (2011). *Efficient treatment of cross-scale interactions in a land-use model*. PhD thesis, Humboldt-Universität zu Berlin.

EC-JRC/PBL (2011). Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2. Available from: `http://edgar.jrc.ec.europa.eu.`, 2013-01-10 12:36:38.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magne, B., Scrieciu, S., Turton, H., and Vuuren, D. P. V. (2010a). The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. *The Energy Journal*, 31(01):11–48.

Edenhofer, O., Pichs-Madruga, R., Barros, Y. S. V., Field, C. B., Zwickel, T., Schlömer, S., Ebi, K., Mastrandrea, M., Mach, K. J., and von Stechow, C. (2010b). IPCC Workshop on Socio-Economic Scenarios - Workshop Report. Technical report, Intergobernmental Panel on Climate Change (IPCC), Berlin.

Eggleston, S., Paustian, K., Ravindranath, N., and van Amstel, A. (2006). Volume 4: Agriculture, Forestry and Other Land Use. In *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Institute for Global Environmental Strategies (IGES), Hayama, Japan.

Ehrlich, P. R. and Holdren, J. P. (1971). Impact of population growth. *Science*, 171:1212–1217.

Ehrlich, P. R. and Pringle, R. M. (2008). Colloquium paper: where does biodiversity go from here? A grim business-as-usual forecast and a hopeful portfolio of partial solutions. *Proceedings of the National Academy of Sciences of the United States of America*, 105(Suppl. 1):11579–11586.

EMF (2013). Energy Modeling Forum (EMF). Available from: `http://emf.stanford.edu/`, 2013-05-03 12:35:33.

EPA (2006). Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990/2020. Technical report, United States Environmental Protection Agency, Washington, D.C.

Erb, K., Mayer, A., Kastner, T., Sallet, K., and Haberl, H. (2012). The impact of industrial grain fed livestock production on food security: An extended literature review. Technical report, Alpen-Adria Universität, Klagenfurt.

Erb, K.-H., Gaube, V., Krausmann, F., Plutzar, C., Bondeau, A., and Haberl, H. (2007). A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. *Journal of Land Use Science*, 2(3):191–224.

Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research. *Global Environmental Change*, 18(1):234–245.

Evenson, R. E. and Gollin, D. (2003). Assessing the impact of the green revolution, 1960 to 2000. *Science*, 300:758–762.

Ewert, F., Rounsevell, M., Reginster, I., Metzger, M., and Leemans, R. (2005). Future scenarios of European agricultural land use. *Agriculture, Ecosystems and Environment*, 107(2-3):101–116.

FAO (2010). Sustainable crop production intensification through an ecosystem approach and an enabling environment: capturing efficiency through ecosystem services and management. Technical report, FAO Committee on Agriculture, Food and Agriculture Organization of the United Nations, Rome.

FAO (2011). Climate-Smart Agriculture : A Synthesis of Empirical Evidence of Food Security and Mitigation Benefits from Improved Cropland Management. Technical report, Food and Agriculture Organization of the United Nations.

FAO (2012). Feeding the world. In *FAO Statistical Yearbook 2012*, chapter Part 3, pages 171–181. Food and Agriculture Organization of the United Nations.

FAOSTAT (2011). Database Collection of the Food and Agriculture Organization of the United Nations. Available from: `www.faostat.fao.org`, 2013-02-15 13:31:55.

FAOSTAT (2012). Database Collection of the Food and Agriculture Organization of the United Nations. Food Balance Sheets. Available from: `http://faostat3.fao.org/home/index.html`, 2013-02-15 13:34:39.

Fargione, J., Hill, J., Tilman, D., Polasky, S., and Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science (New York, N.Y.)*, 319:1235–1238.

Feng, W., Cai, Y., and Gu, B. (2013). Population, Policy, and Politics: How Will History Judge China ' s One-Child Policy? *Population and Development Review*, 38(Suppl.):115–129.

Field, C. B., Campbell, J. E., and Lobell, D. B. (2008). Biomass energy: the scale of the potential resource. *Trends in ecology & evolution*, 23(2):65–72.

Flynn, H. and Smith, P. (2010). Greenhouse gas budgets of crop production–current and likely future trends. Technical report, International Fertilizer Industry Association.

Fogarty, J. and McCally, M. (2010). Health and safety risks of carbon capture and storage. *Journal of the American Medical Association*, 303(1):67–8.

Foley, J. a., Ramankutty, N., Brauman, K. a., Cassidy, E. S., Gerber, J. S., Johnston, M., Mueller, N. D., O'Connell, C., Ray, D. K., West, P. C., Balzer, C., Bennett, E. M., Carpenter, S. R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., and Zaks, D. P. M. (2011). Solutions for a cultivated planet. *Nature*, 478:337–342.

Foresight (2009). The Future of Food and Farming : Challenges and choices for global sustainability. Technical report, The Government Office for Science, London.

Friel, S., Dangour, A. D., Garnett, T., Lock, K., Chalabi, Z., Roberts, I., Butler, A., Butler, C. D., Waage, J., McMichael, A. J., and Haines, A. (2009). Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. *Lancet*, 374:2016–2025.

Fritz, S., You, L., Bun, A., See, L., McCallum, I., Schill, C., Perger, C., Liu, J., Hansen, M., and Obersteiner, M. (2013). The Need for Improved Maps of Global Cropland. *Eos*, 38(3):31–32.

Gallagher, E. (2008). The Gallagher review of the indirect effects of biofuels production. Technical report, Renewable Fuels Agency.

Gerbens-Leenes, P. and Nonhebel, S. (2002). Consumption patterns and their effects on land required for food. *Ecological Economics*, 42(1-2):185–199.

Gibbs, H. and Ruesch, A. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences of the United States of America*, 107(38):1–6.

Gielen, D., Fujino, J., Hashimoto, S., and Moriguchi, Y. (2003). Modeling of global biomass policies. *Biomass and Bioenergy*, 25(2):177–195.

Gitz, V. and Ciais, P. (2004). Future Expansion Of Agriculture and Pasture Acts to Amplify Atmospheric CO2 Levels in Response to Fossil-Fuel and Land-Use Change Emissions. *Climatic Change*, 67:161–184.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., and Toulmin, C. (2010a). Food security: the challenge of feeding 9 billion people. *Science (New York, N.Y.)*, 327:812–818.

Godfray, H. C. J., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Nisbett, N., Pretty, J., Robinson, S., Toulmin, C., and Whiteley, R. (2010b). The future of the global food system. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 365:2769–2777.

Goldemberg, J. (2007). Ethanol for a sustainable energy future. *Science*, 315:808–810.

Green, R. E., Cornell, S. J., Scharlemann, J. P. W., and Balmford, A. (2005). Farming and the fate of wild nature. *Science*, 307:550–555.

Gustavson, J. and Cederberg, C. (2011). Global Food Losses and Food Waste: Extent, Causes and Prevention. Technical report, Swedish Institute for Food and Biotechnology (SIK), Gothenburg, Sweden. 38.

Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzar, C., and Steinberger, J. K. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass & bioenergy*, 35(12):4753–4769.

Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R. K., Kastrup, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenberg, A., van den Hove, S., Vermeire, T., Wadhams, P., and Searchinger, T. (2012). Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy*, 45:18–23.

Hafner, S. (2003). Trends in maize, rice, and wheat yields for 188 nations over the past 40 years: a prevalence of linear growth. *Agriculture, Ecosystems & Environment*, 97(1-3):275–283.

Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-Saharan Africa. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 360(1463):2169–2182.

Harvey, M. and Pilgrim, S. (2011). The new competition for land: Food, energy, and climate change. *Food Policy*, 36:S40–S51.

Havlík, P., Schneider, U. a., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S. D., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., and Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. *Energy Policy*, 39(10):5690–5702.

Hazell, P. and Wood, S. (2008). Drivers of change in global agriculture. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 363:495–515.

Henle, K., Alard, D., Clitherow, J., Cobb, P., Firbank, L., Kull, T., McCracken, D., Moritz, R. F., Niemelä, J., Rebane, M., Wascher, D., Watt, A., and Young, J. (2008). Identifying and managing the conflicts between agriculture and biodiversity conservation in Europe–A review. *Agriculture, Ecosystems & Environment*, 124(1-2):60–71.

Hesketh, T., Lu, L., and Xing, Z. (2005). The effect of China's one-child family policy after 25 years. *New England Journal of Medicine*, 353(11):1171–1176.

Huber, V., Neher, I., Bodirsky, B. L., and Höfner, K. (2013). Will the world run out of land? A Kaya-like-decomposition to study past trends of cropland expansion. *submitted*.

IIASA (2013). IIASA Database. Available from: `https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=series`, 2013-03-10 10:12:01.

IPCC (1996). Agriculture. In *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, chapter 4. Institute for Global Environmental Strategies (IGES).

IPCC (2007). IPCC Fourth Assessment Report (AR4) - Working Group III: Climate Change 2007. Technical Report 4, Intergovernmental Panel on Climate Change.

Janzen, H. (2004). Carbon cycling in earth systems—a soil science perspective. *Agriculture, Ecosystems & Environment*, 104(3):399–417.

Kastner, T., Rivas, M. J. I., Koch, W., and Nonhebel, S. (2012). Global changes in diets and the consequences for land requirements for food. *Proceedings of the National Academy of Sciences of the United States of America*, 109(18):6868–6872.

Kates, R. W. (2000). Population and Consumption - What we know, what we need to know. *Environment*, 6:44–51.

Kearney, J. (2010). Food consumption trends and drivers. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 365:2793–2807.

Krausmann, F., Erb, K.-H., Gingrich, S., Lauk, C., and Haberl, H. (2008). Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics*, 65(3):471–487.

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., and Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, 22(4):807–822.

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., and Ward, P. J. (2012). Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *The Science of the total environment*, 438:477–89.

Lal, R. (2003). Offsetting global CO2 emissions by restoration of degraded soils and intensification of world agriculture and forestry. *Land Degradation & Development*, 14(3):309–322.

Lambin, E. F. and Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, 108(9):3465–72.

Leimbach, M., Bauer, N., Baumstark, L., and Edenhofer, O. (2009). Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R. *Environmental Modeling & Assessment*, 15(3):155–173.

Liu, J., Daily, G. C., Ehrlich, P. R., and Luck, G. W. (2003). Effects of household dynamics on resource consumption and biodiversity. *Nature*, 421:530–533.

Lotze-Campen, H., Mueller, C., Bondeau, A., Rost, S., Popp, A., and Lucht, W. (2008). Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agricultural Economics*, 39:325–338.

Luderer, G., Pietzcker, R. C., Kriegler, E., Haller, M., and Bauer, N. (2012). Asia's role in mitigating climate change: A technology and sector specific analysis with ReMIND-R. *Energy Economics*, 34:S378–S390.

Lutz, W. and K. C., S. (2010). Dimensions of global population projections: What do we know about future population trends and structures? *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 365:2779–2791.

Lutz, W. and Kc, S. (2011). Global human capital: Integrating education and population. *Science*, 333:587–592.

Lutz, W., Sanderson, W., and Scherbov, S. (1997). Doubling of world population unlikely. *Nature*, 387:803–805.

Lutz, W., Sanderson, W., and Scherbov, S. (2001). The end of world population growth. *Nature*, 412:543–545.

Manne, A. and Richels, R. (1998). The Kyoto Protocol: A cost-effective strategy for meeting environmental objectives. Technical report, Stanford University.

McDougall, R. A., Elbehri, A., and Truong, T. (1998). Global Trade, Assistance, and Production: The GTAP 4 Data Base. Technical report, Purdue University. Center for Global Trade Analysis.

Moldanová, J., Grennfelt, P., Jonsson, A. s., Simpson, D., Spranger, T., Aas, W., Munthe, J., and Rabl, A. (2011). Nitrogen as a threat to European air quality. In *The European Nitrogen Assessment - Sources, Effects and Policy Perspectives*, chapter 18, pages 405–433. Cambridge University Press.

Mosier, A. R., Duxbury, J. M., Freney, J. R., Heinemeyer, O., Minami, K., and Johnson, D. E. (1998). Mitigating agricultural emissions of methane. *Climate Change*, 40(1):39–80.

Mueller, A. and Schmidhuber, J. (2008). Some insights in the effect of growing bio-energy demand on global food security and natural resources. *Water Policy*, 10(1):83–94.

Naik, S., Goud, V. V., Rout, P. K., and Dalai, A. K. (2010). Production of first and second generation biofuels: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 14(2):578–597.

Nordström, H. k. and Vaughan, S. (2000). *Trade and the environment - Special Studies*, volume 5. World Trade Organization.

OECD and FAO (2011). OECD-FAO Agricultural Outlook 2011-2020. Technical report, Organisation for economic co-operation and development and Food and agriculture organization of the united nations.

Ogle, S., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., Mccarl, B., Ogle, S., Rice, C., Scholes, B., Sirotenko, O., Davidson, O. R., Bosch, P. R., and Dave, R. (2007). Agriculture. In *IPCC Fourth Assessment Report (AR4) - Working Group III: Climate Change 2007*, chapter 8. Intergovernmental Panel on Climate Change.

Oldeman, L., Hakkeling, R. T. A., and Sombroek, W. G. (1999). World map of the status of human–induced soil degradation. Technical report, Global Assessment of Soil Degradation GLASOD. 1–41.

Olesen, J., Schelde, K., Weiske, a., Weisbjerg, M., Asman, W., and Djurhuus, J. (2006). Modelling greenhouse gas emissions from European conventional and organic dairy farms. *Agriculture, Ecosystems & Environment*, 112(2-3):207–220.

O'Mara, F. (2011). The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. *Animal Feed Science and Technology*, 166-167:7–15.

O'Neill, B., Carter, T. R., Ebi, K. L., Edmonds, J., Hallegatte, S., Kemp-Benedict, E., Kriegler, E., Mearns, L., Moss, R., Riahi, K., van Ruijven, B., and van Vuuren, D. (2012). Meeting Report of the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research. Technical report, National Center for Atmospheric Research (NCAR). 1–37.

Parfitt, J., Barthel, M., and Macnaughton, S. (2010). Food waste within food supply chains: quantification and potential for change to 2050. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 365:3065–3081.

Paustian, K., Six, J., Elliott, E., and Hunt, H. (2000). Management options for reducing CO2 emissions from agricultural soils. *Biogeochemistry*, 48:147–163.

Popp, A., Dietrich, J. P., Lotze-Campen, H., Klein, D., Bauer, N., Krause, M., Beringer, T., Gerten, D., and Edenhofer, O. (2011). The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environmental Research Letters*, 6(3):034017.

Popp, A., Krause, M., Dietrich, J. P., Lotze-Campen, H., Leimbach, M., Beringer, T., and Bauer, N. (2012). Additional CO2 emissions from land use change — Forest conservation as a precondition for sustainable production of second generation bioenergy. *Ecological Economics*, 74:64–70.

Popp, A., Lotze-Campen, H., and Bodirsky, B. (2010). Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. *Global Environmental Change*, 20(3):451–462.

Pretty, J., Toulmin, C., and Williams, S. (2011). Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, 9(1):5–24.

R (2013). The R Project for Statistical Computing. Available from: `http://www.r-project.org/`.

Ramankutty, N. and Foley, J. a. (1998). Characterizing patterns of global land use: An analysis of global croplands data. *Global Biogeochemical Cycles*, 12(4):667–685.

Ramankutty, N., Foley, J. a., and Olejniczak, N. J. (2002). People on the land: Changes in global population and croplands during the 20th century. *Ambio: A Journal of the Human Environment*, 31(3):251–257.

Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Dorland, R. V., Qin, D., Manning, M., Chen, Z., Marquis, M., and Averyt, K. B. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In Teruyuki Nakajima (Japan), V. R. U., editor, *IPCC Fourth Assessment Report*, chapter 2, pages 129 – 232. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Raupach, M. and Marland, G. (2007). Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 104(24):10288–10293.

Reay, D. S., Davidson, E. a., Smith, K. a., Smith, P., Melillo, J. M., Dentener, F., and Crutzen, P. J. (2012). Global agriculture and nitrous oxide emissions. *Nature Climate Change*, 2(6):410–416.

Rockström, J. (2009). A safe operating space for humanity. *Nature*, 461:472–475.

Rockström, J., Kemp-Benedict, E., Wichelns, D., Kemp-benedict, E., Gordon, L. J., Hanjra, M. A., Hoogeveen, J., Huber-lee, A., and Karlberg, L. (2007). Looking ahead to 2050: scenarios of alternative investment approaches. In *Water for food, water for life: A comprehensive assessment of water management in agriculture*, chapter 3, pages 91–145. Routledge, London, UK: Earthscan, and Colombo, Sri Lanka: International Water Management Institute,.

Rosegrant, M., Paisner, M., and Meijer, S. (2001a). Long Term Prospects for Agriculture and the Resource Base. Technical report, The World Bank Rural Development Family. Rural Development Strategy Background Paper #1. The World Bank, Washington.

Rosegrant, M., Paisner, M., Meijer, S., and Witcover, J. (2001b). *Global food projections to 2020: emerging trends and alternative futures.* International Food Policy Research Institute.

Rozemeijer, J. C. and Broers, H. P. (2007). The groundwater contribution to surface water contamination in a region with intensive agricultural land use (Noord-Brabant, The Netherlands). *Environmental pollution (Barking, Essex: 1987)*, 148(3):695–706.

Rudel, T. K., Schneider, L., Uriarte, M., Turner, B. L., DeFries, R., Lawrence, D., Geoghegan, J., Hecht, S., Ickowitz, A., Lambin, E. F., Birkenholtz, T., Baptista, S., and Grau, R. (2009). Agricultural intensification and changes in cultivated areas, 1970-2005. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49):20675–20680.

Sala, O. E. (2000). Global Biodiversity Scenarios for the Year 2100. *Science*, 287:1770–1774.

Sarkar, S., Pfeifer, J., and Garson, J. (2006). *The philosophy of science: an encyclopedia. NZ, Indeks*. The Philosophy of Science: An Encyclopedia. Routledge, Taylor & Francis Group, New York, London.

Schellnhuber, H. J. (1999). 'Earth system' analysis and the second Copernican revolution. *Nature*, 402(Supp):C19–C23.

Schlegel, S. and Kaphengst, T. (2007). European Union Policy on Bioenergy and the Role of Sustainability Criteria and Certification Systems. *Journal of Agricultural & Food Industrial Organization*, 5(2):7.

Schmidhuber, J. and Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 104(50):19703–19708.

Schmitz, C., Biewald, A., Lotze-Campen, H., Popp, A., Dietrich, J. P., Bodirsky, B., Krause, M., and Weindl, I. (2012). Trading more food: Implications for land use, greenhouse gas emissions, and the food system. *Global Environmental Change*, 22(1):189–209.

Schmitz, C., van Meijl, H., Kyle, P., Fujimori, S., Gurgel, A., Havlik, P., D'Croz, D. M., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., and Valin, H. (2013). How much cropland is needed ? - Insights from a global agro-economic model comparison. *submitted*.

Schubert, R., Schellnhuber, H., Buchmann, N., Epiney, A., Grieß hammer, R., Kulessa, M., Messner, D., Rahmstorf, S., and Schmid, J. (2010). *Future bioenergy and sustainable land use*. WBGU - German Advisory Council on Global Change, Earthscan, London and Sterling, VA, London.

Sims, R., Taylor, M., Saddler, J., and Mabee, W. (2008). From 1st- to 2nd-Generation Biofuel Technologies: An overview of current industry and RD&D activities. Technical report, International Energy Agency (IEA).

Sitch, S., Smith, B., Prentice, I. C., Arneth, a., Bondeau, a., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, 9(2):161–185.

Smil, V. (2000). *Feeding the World: A Challenge for the 21st century.* The MIT Press.

Smit, A. and Bindraban, P. (2009). Phosphorus in agriculture: global resources, trends and developments. Technical report, Plant Resaerch International, Wageningen.

Smith, P., Gregory, P. J., van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., and Bellarby, J. (2010). Competition for land. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 365:2941–2957.

SREEN (2012). Renewable Energy Sources and Climate Change Mitigation Special Report of the Intergovernmental Panel on Climate Change. Technical report, Intergovernmental Panel on Climate Change.

SRES (2000). IPCC Special Report on Emission Scenarios. Technical report, Intergovernmental Panel on Climate Change.

Steckel, J. C., Jakob, M., Marschinski, R., and Luderer, G. (2011). From carbonization to decarbonization?—Past trends and future scenarios for China's CO2 emissions. *Energy Policy*, 39(6):3443–3455.

Stehfest, E., Bouwman, L., Vuuren, D. P., Elzen, M. G. J., Eickhout, B., and Kabat, P. (2009). Climate benefits of changing diet. *Climatic Change*, 95:83–102.

Sun, J. (1998). Accounting for energy use in China, 1980–94. *Energy*, 23(10):835–849.

Sun, J. and Ang, B. (2000). Some properties of an exact energy decomposition model. *Energy*, 25:1177–1188.

Taheripour, F., Hurt, C., and Tyner, W. E. (2013). Livestock industry in transition: Economic, demographic, and biofuel drivers. *Animal Frontiers*, 3(2):38–46.

Tao, L. and Aden, A. (2009). The economics of current and future biofuels. *In Vitro Cellular & Developmental Biology - Plant*, 45(3):199–217.

Tilman, D. and Balzer, C. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, 108(50):20260–20264.

Tilman, D., Cassman, K. G., Matson, P. a., Naylor, R., and Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, 418:671–677.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W. H., Simberloff, D., and Swackhamer, D. (2001). Forecasting agriculturally driven global environmental change. *Science (New York, N.Y.)*, 292:281–284.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., and Williams, R. (2009). Beneficial Biofuels—The Food, Energy, and Environment Trilemma. *Science*, 325:4–5.

Tscharntke, T., Clough, Y., Wanger, T. C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., and Whitbread, A. (2012). Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation*, 151(1):53–59.

UN (2012). World Population Prospects, the 2010 Revision. Available from: `http://esa.un.org/wpp/Analytical-Figures/htm/fig_1.htm`, 2013-02-22 11:22:47.

UNFPA (2012). Population Trends: Rapid Growth in Less Developed Regions: Population & Development : UNFPA. Available from: `http://www.unfpa.org/pds/trends.htm`, 2013-02-28 11:30:22.

Van Der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G. J., Kasibhatla, P. S., Jackson, R. B., Collatz, G. J., and Randerson, J. T. (2009). CO2 emissions from forest loss. *Nature Geoscience*, 2(11):737–738.

Velthof, G., Bloem, J., Butterbach-bahl, K., Vries, W. D., Kros, J., Lavelle, P., and Oenema, O. (2011). Nitrogen as a threat to European soil quality. In *The European Nitrogen Assessment - Sources, Effects and Policy Perspectives*, chapter 21, pages 495–510. Cambridge University Press.

Verburg, R., Stehfest, E., Woltjer, G., and Eickhout, B. (2009). The effect of agricultural trade liberalisation on land-use related greenhouse gas emissions. *Global Environmental Change*, 19(4):434–446.

Waggoner, P. E. (1995). How much land can ten billion people spare for nature? Does technology make a difference? *Technology in Society*, 17(1):17–34.

Waggoner, P. E. and Ausubel, J. H. (2002). A framework for sustainability science: a renovated IPAT identity. *Proceedings of the National Academy of Sciences of the United States of America*, 99(12):7860–7865.

Wallace, J. S. and Gregory, P. J. (2002). Water resources and their use in food production systems. *Aquatic Sciences*, 64(4):363–375.

Watson, R. T., Zakri, A., Arico, S., Bridgewater, P., Tschirley, J., Valentini, R., Almeida, F., Barnard, P., Camac-ramirez, E., Fortier, F., Schei, P. J., and Mooney, H. A. (2005). Ecosystem and human well-being. Technical report, World Health Organisation.

Webb, P. (2010). Medium-to long-run implications of high food prices for global nutrition. *The Journal of nutrition*, 140:143–147.

Weindl, I. (2010). Impacts of livestock feeding technologies on greenhouse gas emissions.

Wirsenius, S., Azar, C., and Berndes, G. (2010). How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? *Agricultural Systems*, 103(9):621–638.

Wirsenius, S., Hedenus, F., and Mohlin, K. (2011). Greenhouse gas taxes on animal food products: rationale, tax scheme and climate mitigation effects. *Climatic Change*, 108:159–184.

World Bank Group (2007). Population issues in the 21st century, The Role of the World Bank. Technical Report 4-5, World Bank. 315–24.

Zhuang, Q. and Melack, J. (2009). Global methan emissions from wetlands, rice paddies, and lakes. *Eos, Transactions, American Geophysical Union*, 90(5):37–44.

A Decomposition of future emissions on a regional scale

A.1 CO_2 emissions - SSP2 baseline scenario

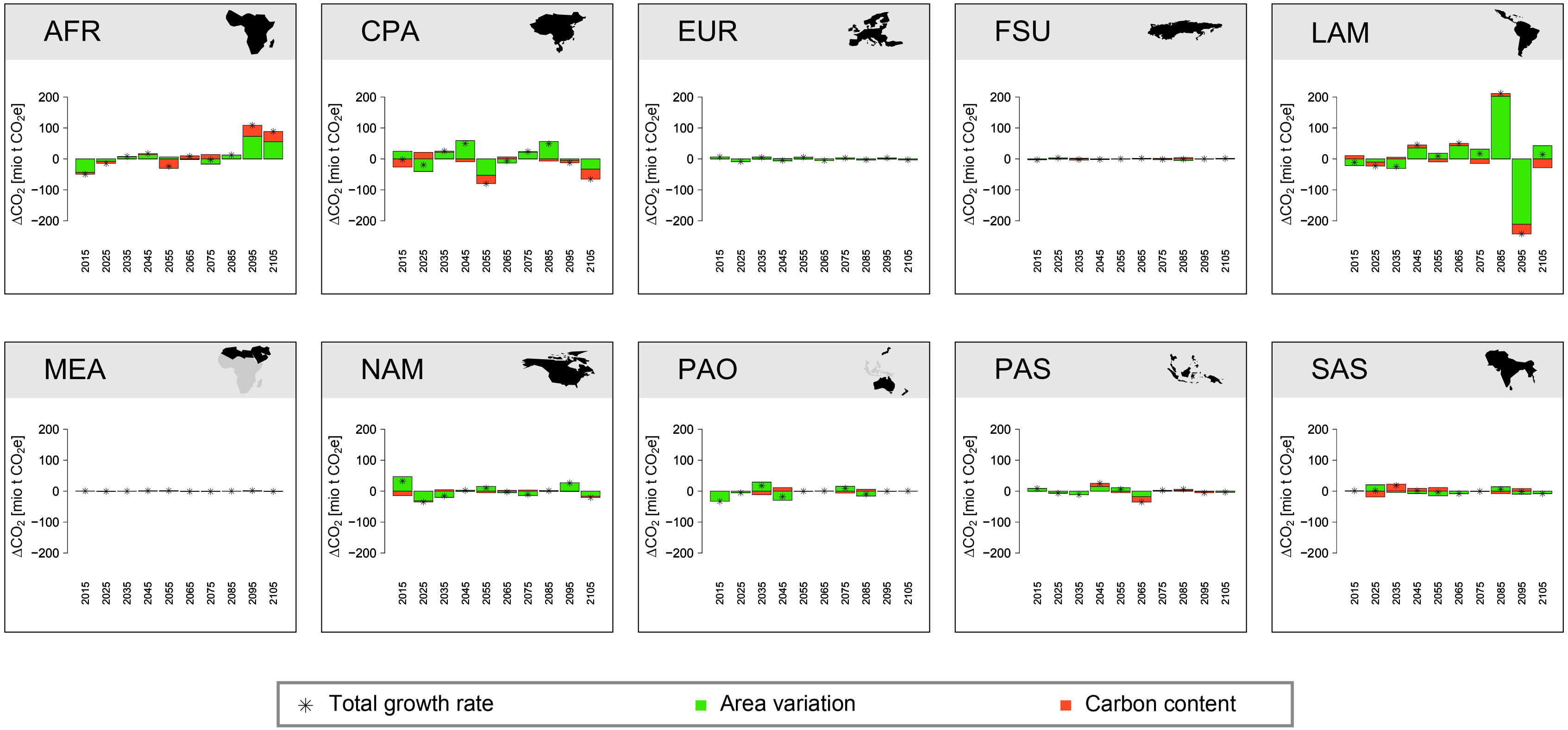

Figure A.1 – Decomposition of yearly growth rates for CO_2 emissions (black stars) in the SSP2 baseline scenario for all 10 world regions. Bars indicate contributions from changes in area variation (green) and carbon content (red); see Eq. 3.14.

A.2 CO_2 emissions - SSP2 mitigation scenario

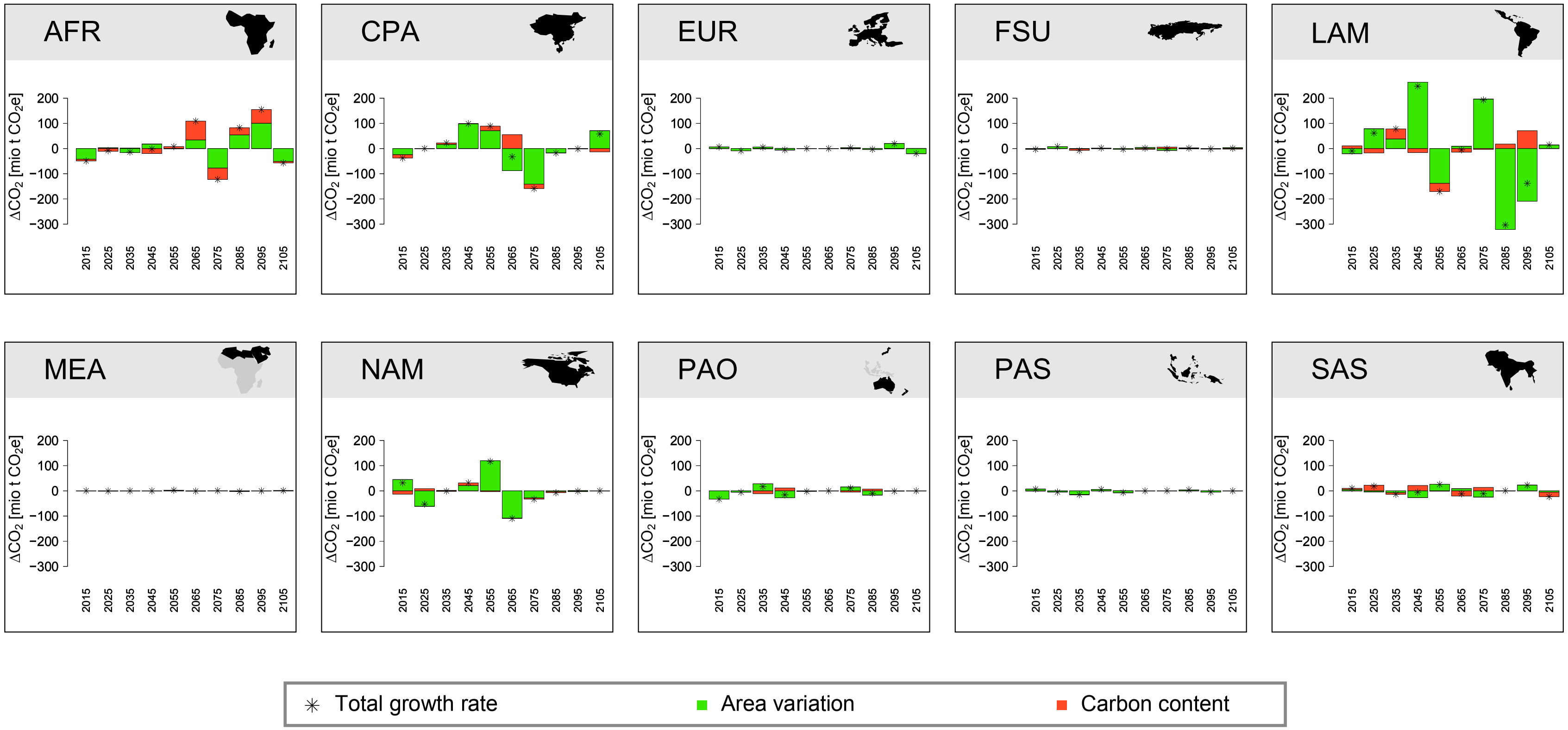

Figure A.2 – Decomposition of yearly growth rates for CO_2 emissions (black stars) in the SSP2 mitigation scenario for all 10 world regions. Bars indicate contributions from changes in area variation (green) and carbon content (red); see Eq. 3.14.

A.3 CH_4 emissions - SSP2 baseline scenario

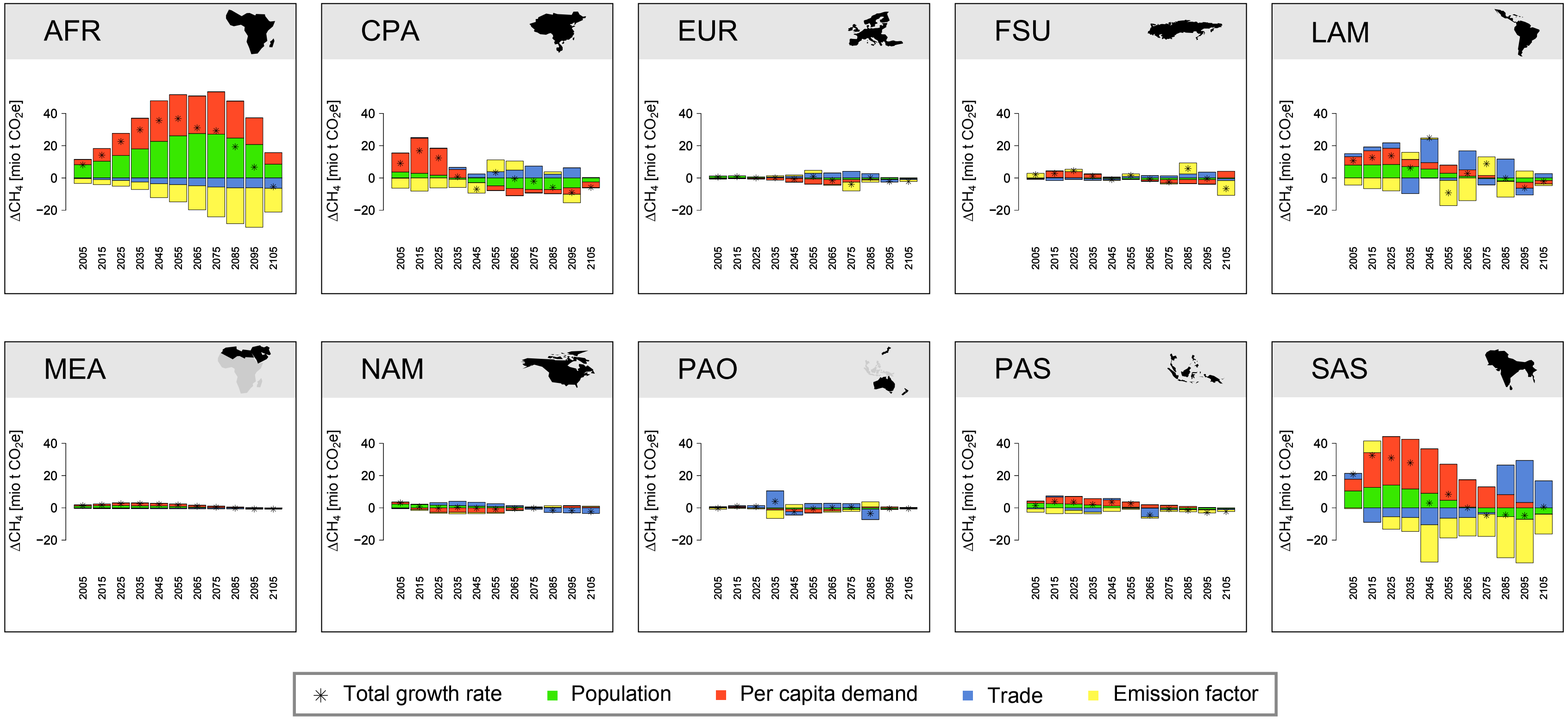

Figure A.3 – Decomposition of yearly growth rates for CH_4 emissions (black stars) in the SSP2 baseline scenario for all 10 world regions. Bars indicate contributions from changes in population (green), per capita demand (red) and emission factor (yellow); see Eq. 3.18.

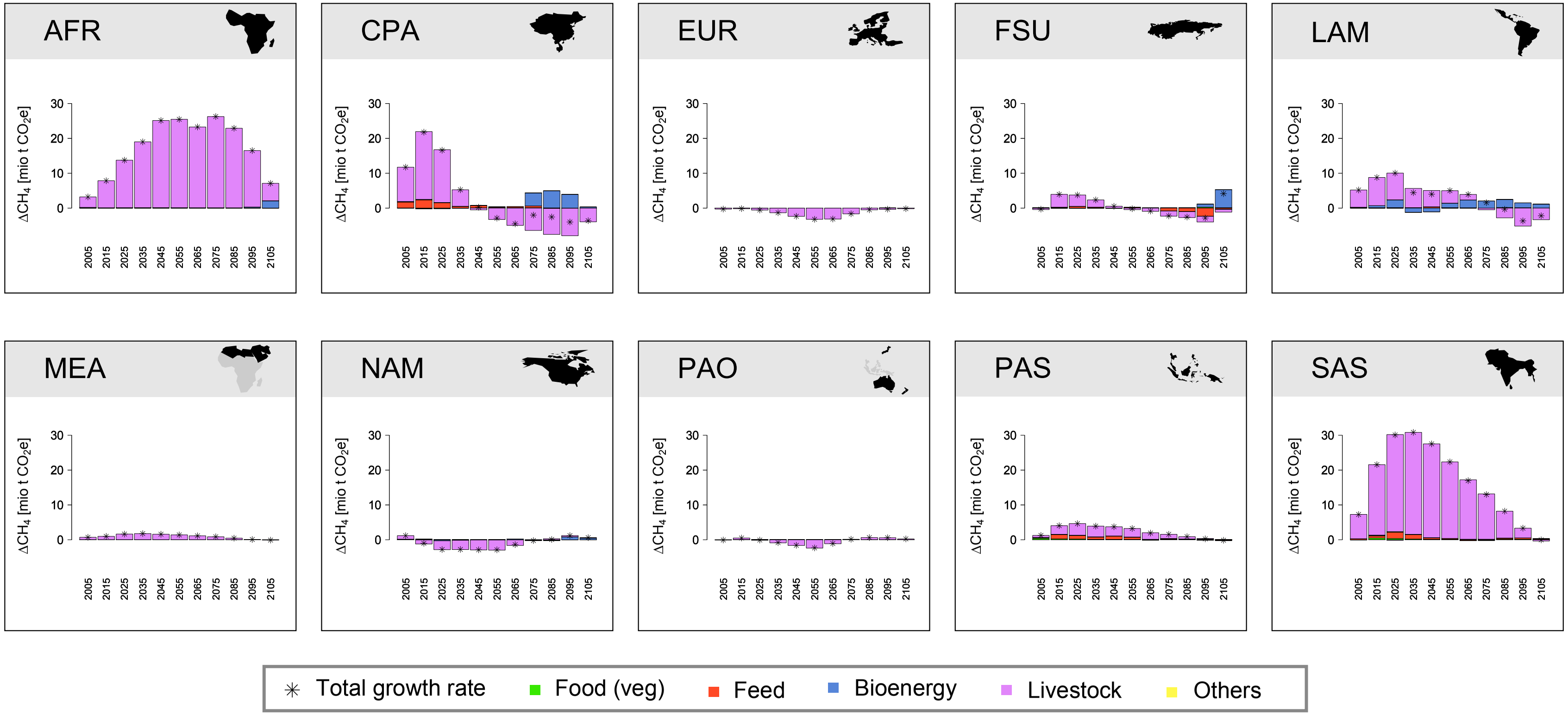

Figure A.4 – Decomposition of yearly growth rates for the influences of per capita demand on CH_4 emissions (black stars) in the SSP2 baseline scenario for all 10 world regions. Bars indicate contributions from changes in food (green), feed (red), bioenergy (blue) and others (yellow) as well as livestock management (magenta) in the further decomposition (below); see Eq. 3.7.

A.4 CH_4 emissions - SSP2 mitigation scenario

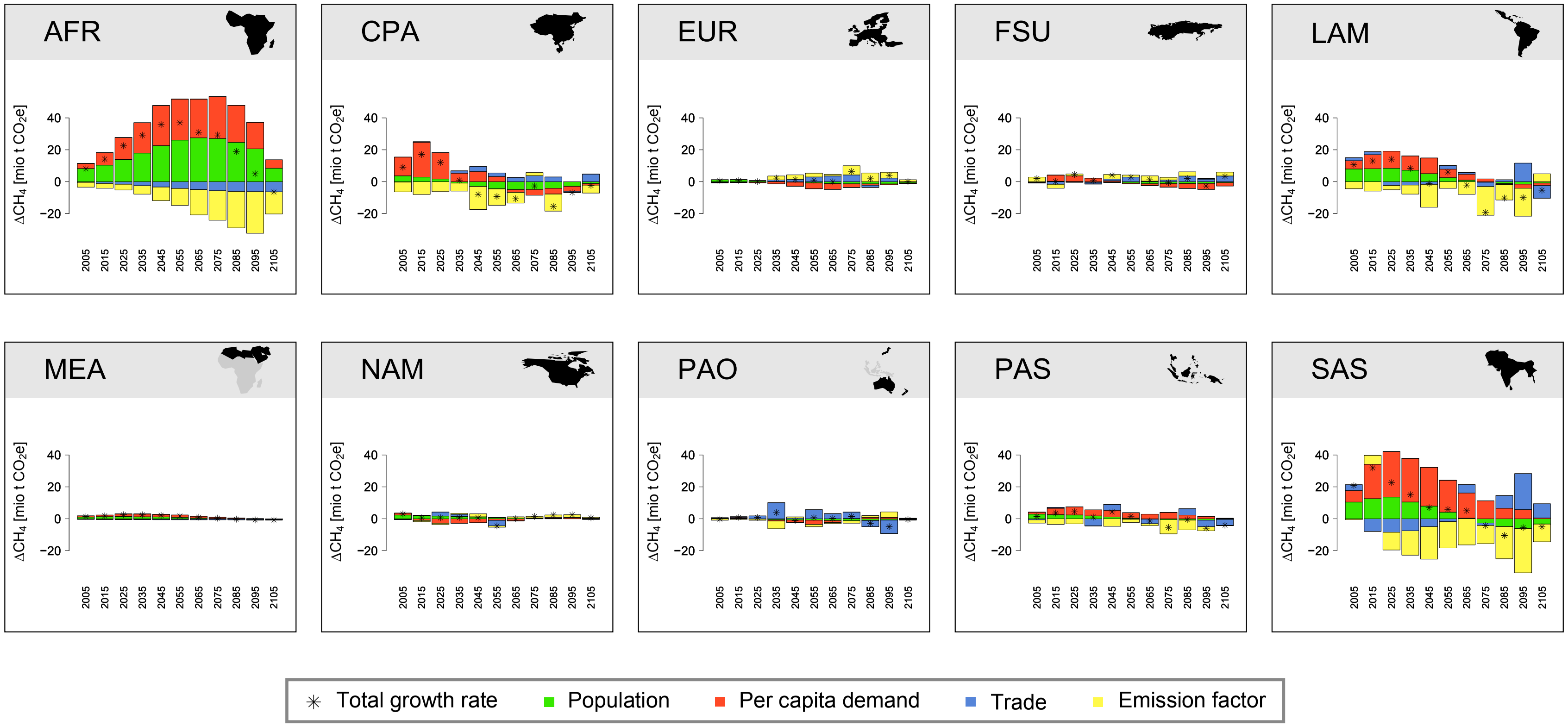

Figure A.5 – Decomposition of yearly growth rates for CH_4 emissions (black stars) in the SSP2 mitigation scenario for all 10 world regions. Bars indicate contributions from changes in population (green), per capita demand (red) and emission factor (yellow); see Eq. 3.18.

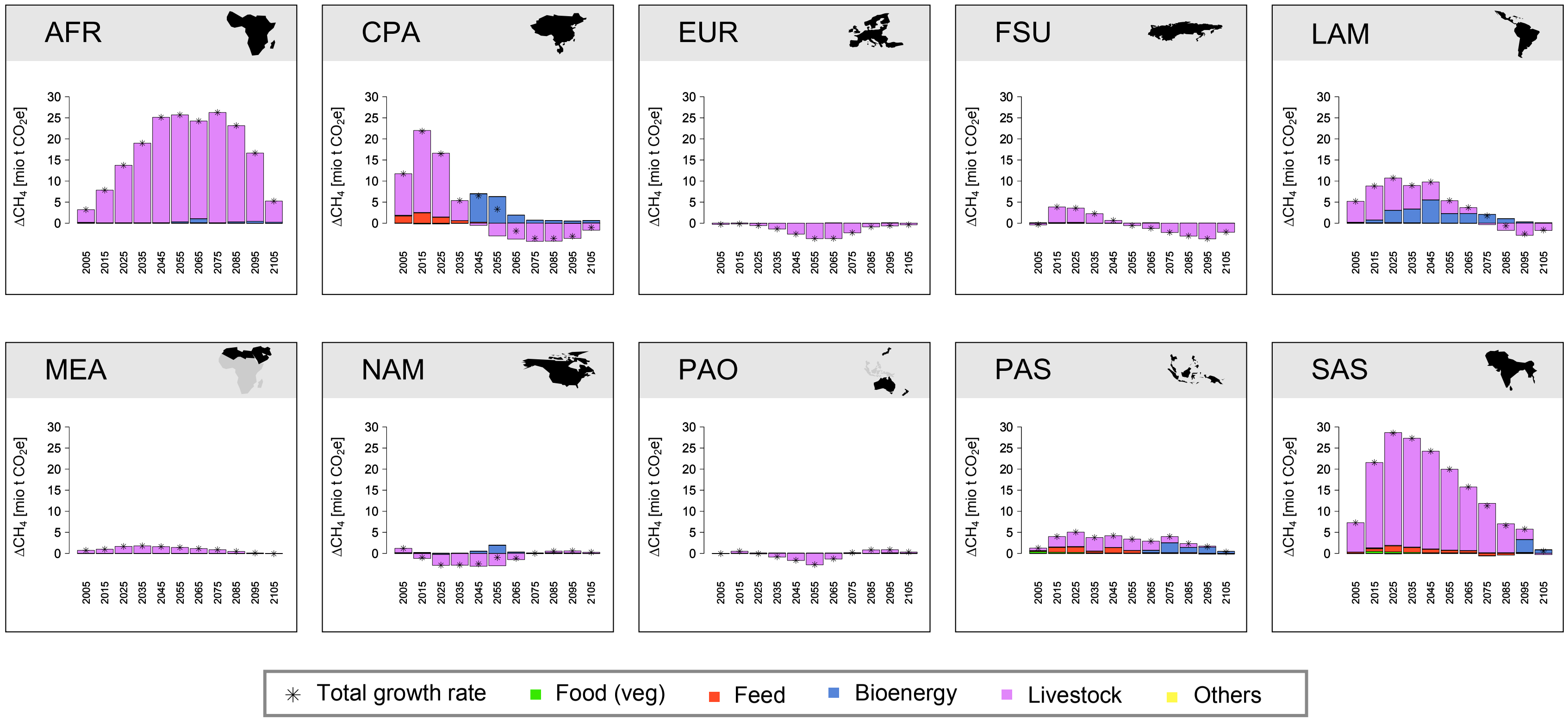

Figure A.6 – Decomposition of yearly growth rates for the influences of per capita demand on CH_4 emissions (black stars) in the SSP2 mitigation scenario for all 10 world regions. Bars indicate contributions from changes in food (green), feed (red), bioenergy (blue) and others (yellow) as well as livestock management (magenta) in the further decomposition (below); see Eq. 3.7.

A.5 N_2O emissions - SSP2 baseline scenario

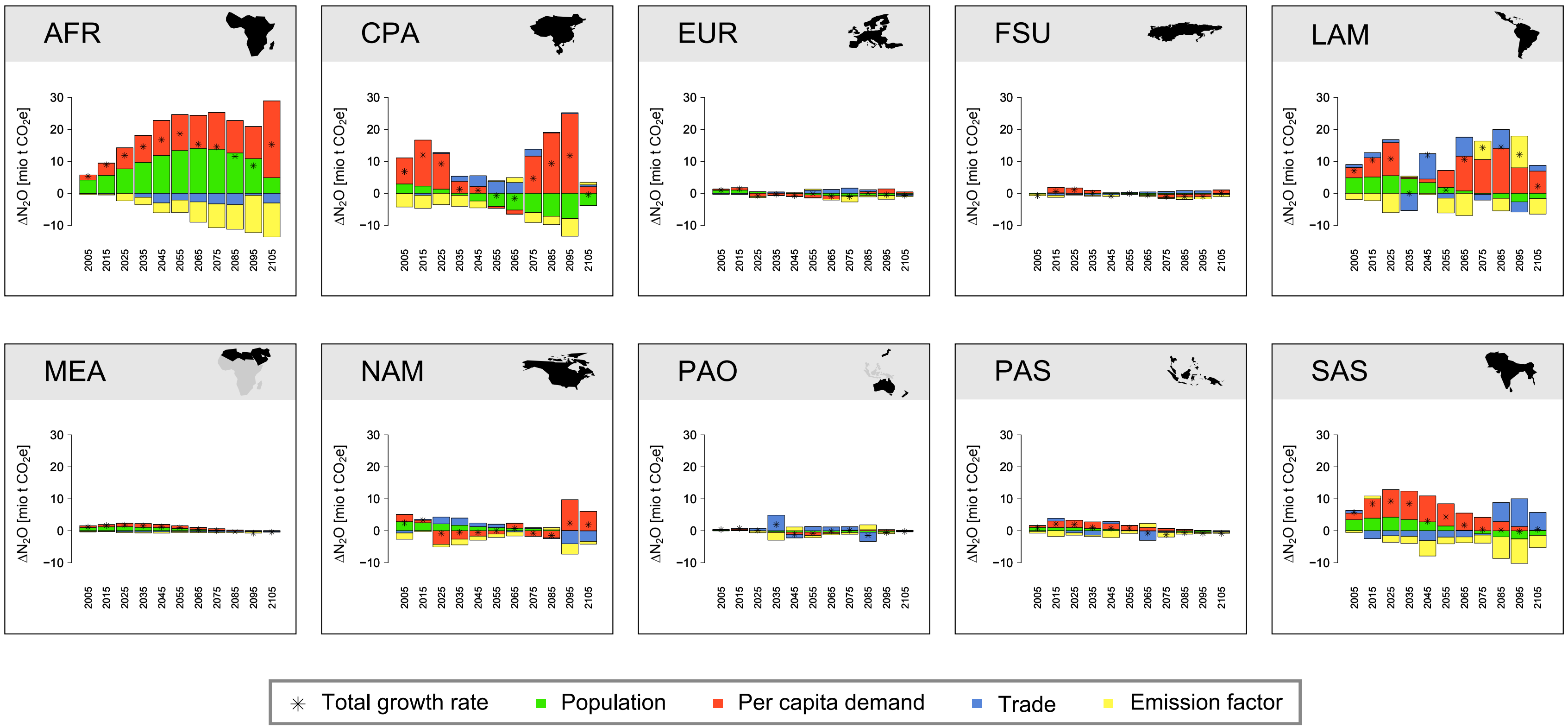

Figure A.7 – Decomposition of yearly growth rates for N_2O emissions (black stars) in the SSP2 baseline scenario for all 10 world regions. Bars indicate contributions from changes in population (green), per capita demand (red) and emission factor (yellow); see Eq. 3.24.

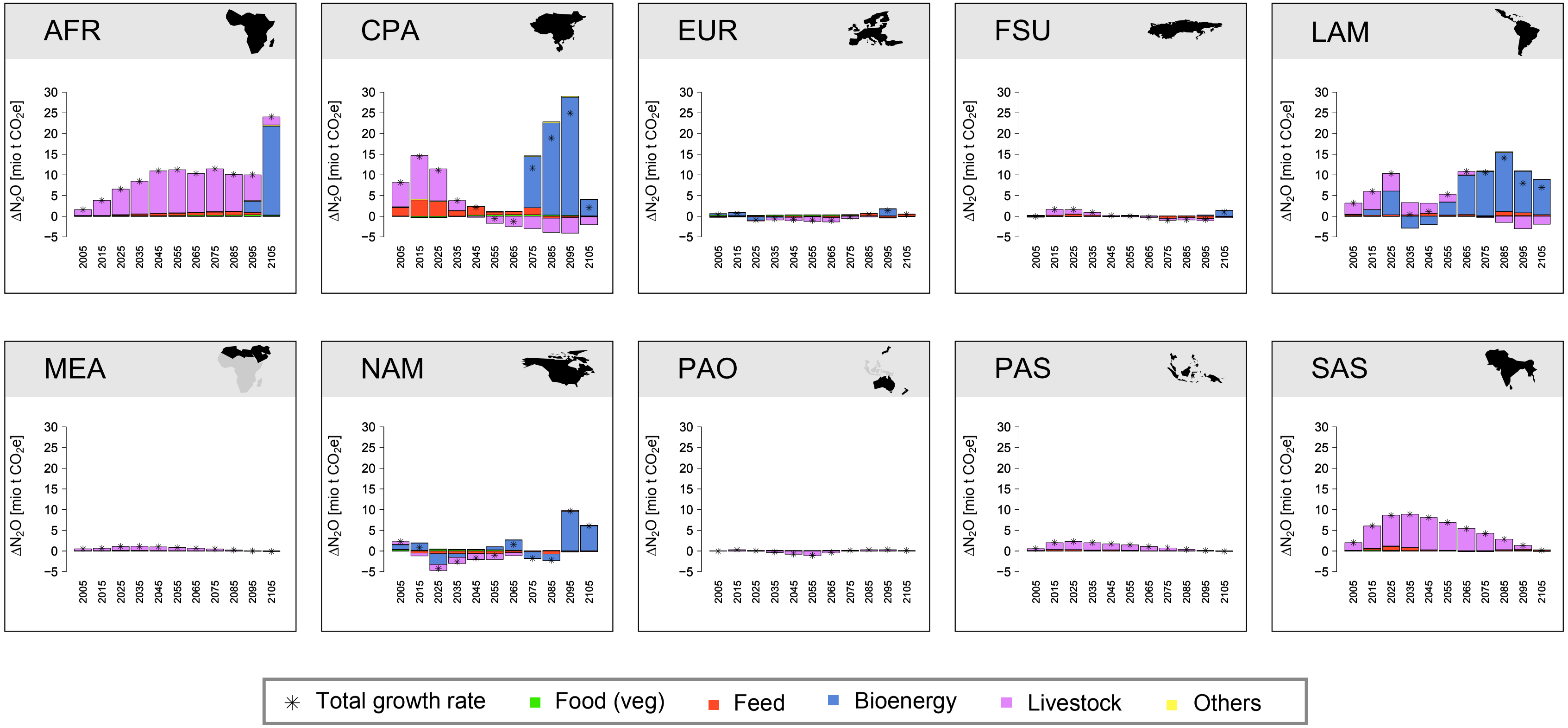

Figure A.8 – Decomposition of yearly growth rates for the influences of per capita demand on N_2O emissions (black stars) in the SSP2 baseline scenario for all 10 world regions. Bars indicate contributions from changes in food (green), feed (red), bioenergy (blue) and others (yellow) as well as livestock management (magenta) in the further decomposition (below); see Eq. 3.7.

A.6 N_2O emissions - SSP2 mitigation scenario

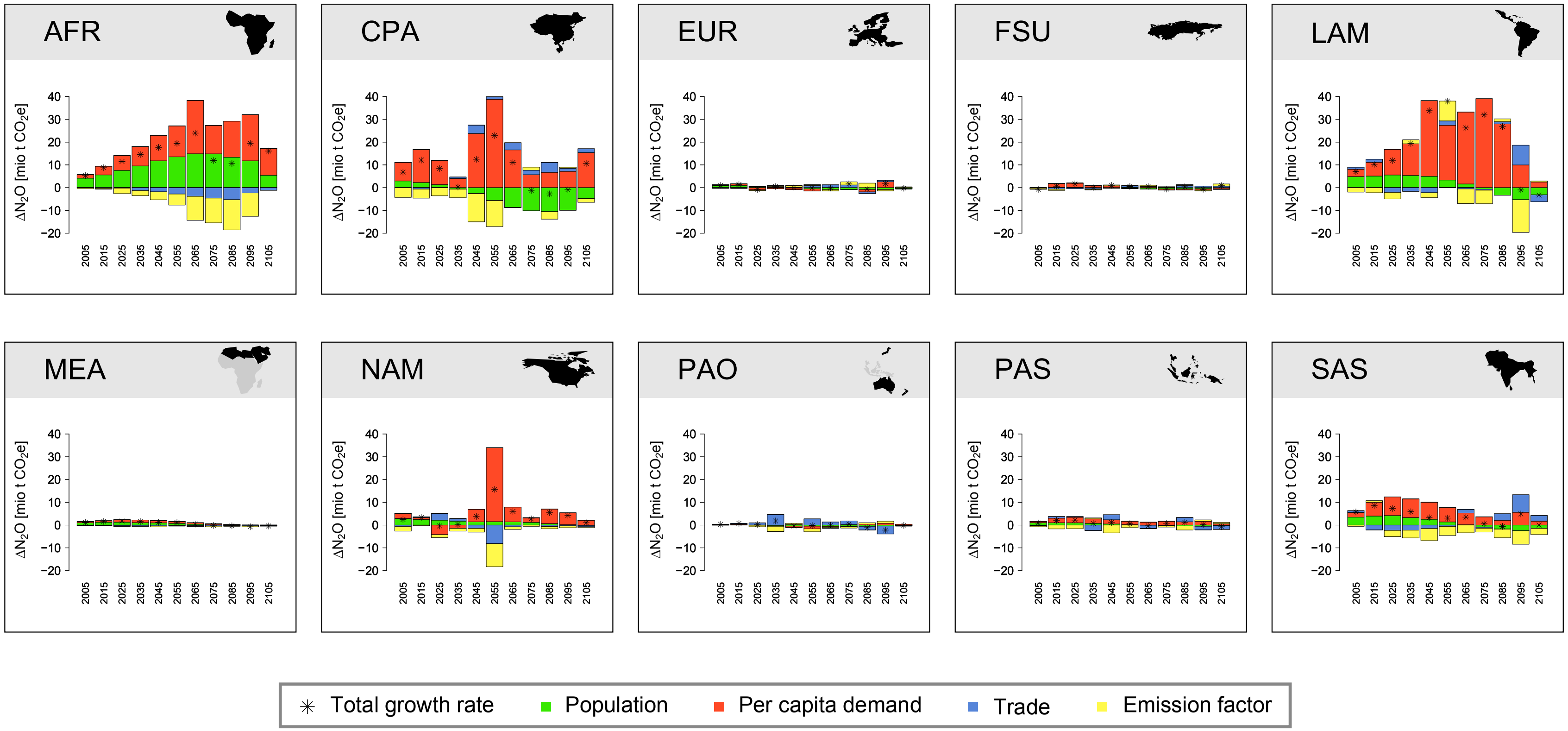

Figure A.9 – Decomposition of yearly growth rates for N_2O emissions (black stars) in the SSP2 mitigation scenario for all 10 world regions. Bars indicate contributions from changes in population (green), per capita demand (red) and emission factor (yellow); see Eq. 3.24.

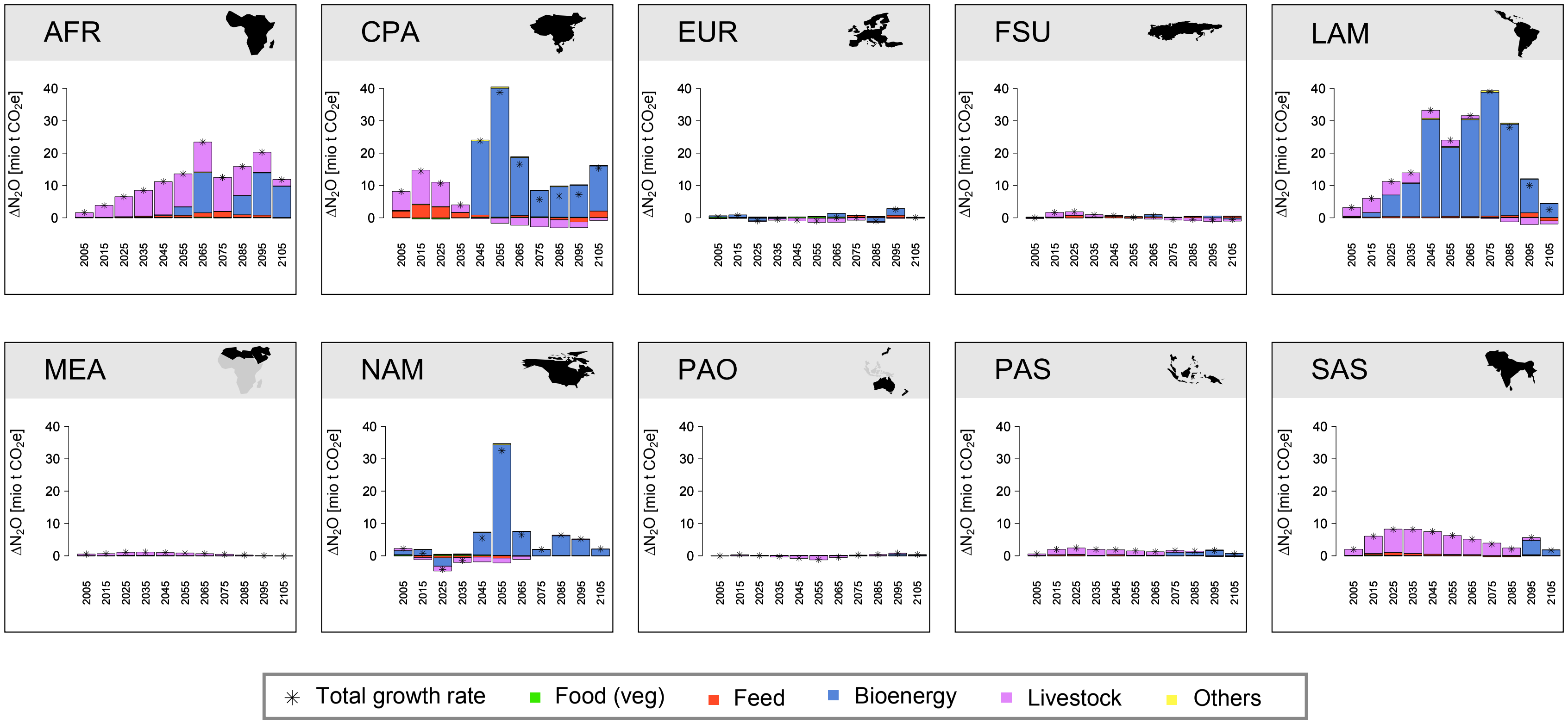

Figure A.10 – Decomposition of yearly growth rates for the influences of per capita demand on N_2O emissions (black stars) in the SSP2 mitigation scenario for all 10 world regions. Bars indicate contributions from changes in food (green), feed (red), bioenergy (blue) and others (yellow) as well as livestock management (magenta) in the further decomposition (below); see Eq. 3.7.

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