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Pathways to future cropland

Assessing uncertainties in socio-economic processes by applying a global land-use model

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Pathways to future cropland

Assessing uncertainties in socio-economic
processes by applying a global land-use model

Kerstin Engström



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DOCTORAL DISSERTATION

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<p>Abstract: Global agricultural production almost tripled within the last five decades. The production increase was based on expanding cropland and pastures, as well as the intensification of agriculture, including increased use of high yielding crop varieties, machinery, irrigation, artificial fertilisers, and pesticides. Both, agricultural intensification and the expansion of agricultural land-use lead to environmental degradation, pose threats to human health, and contribute to climate change. Transitioning towards sustainable agricultural land use, therefore, is one of the major challenges facing humanity in the 21st century. This challenge is aggravated by the need to feed the growing and increasingly affluent population, the effects of climate change on agriculture and the increasing demand for land to mitigate climate change, through for example bioenergy production. This thesis assesses how uncertainties in the development of socio-economic drivers and processes, such as population growth, dietary shifts, technological change, and bioenergy production, affect the outcome of future land-use and land cover change (LULCC). Future development of socio-economic drivers and climate forcing are described by the latest scenarios developed for environmental and climate-change research, i.e. the Shared Socio-economic Pathways (SSPs) and the Representative Concentration Pathways (RCPs). The impacts of the changing drivers on the land system are assessed with the global Parsimonious Land Use Model (PLUM). PLUM was shown to reproduce observed global agricultural land use change at the global to country scale for 1991-2010. Future global cropland changes were found to be very sensitive to the assumed yield growth rate. In a subsequent study, estimates of future yield were therefore derived with a global dynamic vegetation model, and included impacts of climate change. Without assumed land-based mitigation strategies, simulated future cropland ranged from 970 to 2280 Mha by 2100, compared to current cropland area of 1500 Mha. This range is consistent with those found in the recently published literature. Accounting for the uncertainties related to the interpretation of socio-economic processes and drivers described in the scenarios expanded the simulated range for global cropland to 890-2380 Mha (\pm one standard deviation) by 2100 and led to strongly overlapping cropland ranges for three out of five scenarios. Uncertainties related to scenario interpretation are thus of similar importance as uncertainties across different models for estimating the possible outcome of future LULCC. When land-based climate change mitigation strategies are considered, additional cropland requirements of 603-1115 Mha by 2100 were simulated for the production of bioenergy. However, considerable uncertainties related to the strength of mitigation efforts and crop yields accompany this estimate. Continuous expansion of cropland into grasslands and forest, as in scenarios with strong population growth and low technological change or scenarios with large bioenergy production, was simulated to transform the terrestrial biosphere from a carbon sink into a carbon source. Moreover, remaining within the estimated planetary boundary for global cropland (15% of ice-free land) is not possible when aiming to ensure food security while simultaneously producing bioenergy that significantly contributes to strong climate-change mitigation efforts by 2050. In a local to regional case study future food security was shown to be at risk under the assumed future socio-economic developments, demonstrated here for countries in the Sahel region of Africa. Implementing sustainable agricultural management practices as well as global trade will be important to ensure food security in the future. Overall, uncertainties in population development, technological change, resource intensity and land degradation were shown to contribute to a wide range of future agricultural LULCC.</p>			
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Assessing uncertainties in socio-economic processes by applying a global land-use model

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A doctoral thesis at a university in Sweden is produced either as a monograph or a collection of papers. In the latter case, the introductory part constitutes the formal thesis, which summarises the accompanying papers already published or manuscripts at various stages (in press, submitted or in preparation).

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List of papers

- I. Engström, K., Rounsevell, M. D. A., Murray-Rust, D., Hardacre, C., Alexander, P., Cui, X., Palmer, P. I., and Arneth, A. Applying Occam's razor to global agricultural land use change, *Environmental Modelling & Software*, 75, 212-229, 2016.
- II. Engström, K., Olin, S., Rounsevell, M. D. A., Brogaard, S., van Vuuren, D. P., Alexander, P., Murray-Rust, D., and Arneth, A.: Assessing uncertainties in global cropland futures using a conditional probabilistic modelling framework, *Earth System Dynamics Discussions*, 1-33, 2016. *Accepted for publication in ESD subject to minor revisions.*
- III. Engström, K., Lindeskog, M., Olin, S., Hassler, J., Smith, B.: Impacts of climate mitigation strategies in the energy sector on global land use and carbon balance. *Earth System Dynamics Discussions*, 1-43, 2016.
- IV. Engström, K., Olin, S., Rounsevell, M., Arneth, A.: Food supply and bioenergy production within the planetary boundary of global cropland. *Submitted.*
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Contributions

- I. KE is the lead-author of the study and implemented model development. KE and DM-R performed the model simulations. KE prepared the manuscript with contributions from all co-authors.
- II. KE is the lead-author of the study and KE and SO developed the model code and performed the simulations. KE prepared the manuscript with contributions from all co-authors.
- III. KE is the lead-author of the study and implemented model development (PLUM). KE performed the model simulations (climate-economy model and PLUM), KE prepared the manuscript with contributions from all co-authors.
- IV. KE is the lead-author of the study and implemented model development (PLUM). KE and SO performed the model simulations. KE prepared the manuscript with contributions from all co-authors.
- V. KE performed the model simulations (PLUM), contributed to the development of the methodology and the writing of the manuscript.

Abbreviations

AFOLU	Agriculture, Forestry and Other Land Uses
BME	Biome Meta-model Emulator
EC	European Commission
FAO	Food and Agriculture Organisation of the United Nations
FAOSTAT	Statistics division of FAO
GCM	General Circulation Model
GWP	Gross World Product
GDP	Gross Domestic Product
GHG	Green House Gases
GSA	Global Sensitivity Analysis
HICs	High Income Countries
IFAD	International Fund for Agricultural Development
IIASA	International Institute for Applied Systems Analysis
LICs	Low Income Countries
LPJ-GUESS	Lund Potsdam Jena General Ecosystem Simulator
LULCC	Land-Use Land Cover Change
MICs	Middle Income Countries
NECB	Net Ecosystem Carbon Balance
NPP	Net Primary Production
PLUM	Parsimonious Land Use Model
RCP	Representative Concentration Pathway
SOC	Soil Organic Carbon
SPA	Shared Policy Assumption
SRES	Special Report on Emission Scenarios
SSP	Shared Socio-economic Pathways
WFP	World Food Programme
WHO	World Health Organisation

Abstract

Global agricultural production almost tripled within the last five decades. The production increase was based on expanding cropland and pastures, as well as the intensification of agriculture, including increased use of high yielding crop varieties, machinery, irrigation, artificial fertilisers, and pesticides. Both, agricultural intensification and the expansion of agricultural land-use lead to environmental degradation, pose threats to human health, and contribute to climate change. Transitioning towards sustainable agricultural land use, therefore, is one of the major challenges facing humanity in the 21st century. This challenge is aggravated by the need to feed the growing and increasingly affluent population, the effects of climate change on agriculture and the increasing demand for land to mitigate climate change, through for example bioenergy production. This thesis assesses how uncertainties in the development of socio-economic drivers and processes, such as population growth, dietary shifts, technological change, and bioenergy production, affect the outcome of future land-use and land cover change (LULCC). Future development of socio-economic drivers and climate forcing are described by the latest scenarios developed for environmental and climate-change research, i.e. the Shared Socio-economic Pathways (SSPs) and the Representative Concentration Pathways (RCPs). The impacts of the changing drivers on the land system are assessed with the global Parsimonious Land Use Model (PLUM). PLUM was shown to reproduce observed global agricultural land use change at the global to country scale for 1991-2010. Future global cropland changes were found to be very sensitive to the assumed yield growth rate. In a subsequent study, estimates of future yield were therefore derived with a global dynamic vegetation model, and included impacts of climate change. Without assumed land-based mitigation strategies, simulated future cropland ranged from 970 to 2280 Mha by 2100, compared to current cropland area of 1500 Mha. This range is consistent with those found in the recently published literature. Accounting for the uncertainties related to the interpretation of socio-economic processes and drivers described in the scenarios expanded the simulated range for global cropland to 890-2380 Mha (\pm one standard deviation) by 2100 and led to strongly overlapping cropland ranges for three out of five scenarios. Uncertainties related to scenario interpretation are thus of similar importance as uncertainties across different models for estimating the possible outcome of future LULCC. When land-based climate change mitigation strategies are considered, additional cropland requirements of 603-1115 Mha by 2100 were simulated for the production of bioenergy. However, considerable uncertainties related to the strength of mitigation efforts and crop yields accompany this estimate. Continuous expansion of cropland into grasslands and forest, as in scenarios with strong population growth and low technological change or scenarios with large bioenergy

production, was simulated to transform the terrestrial biosphere from a carbon sink into a carbon source. Moreover, remaining within the estimated planetary boundary for global cropland (15% of ice-free land) is not possible when aiming to ensure food security while simultaneously producing bioenergy that significantly contributes to strong climate-change mitigation efforts by 2050. In a local to regional case study future food security was shown to be at risk under the assumed future socio-economic developments, demonstrated here for countries in the Sahel region of Africa. Implementing sustainable agricultural management practices as well as global trade will be important to ensure food security in the future. Overall, uncertainties in population development, technological change, resource intensity and land degradation were shown to contribute to a wide range of future agricultural LULCC.

Zusammenfassung

Innerhalb der letzten fünf Jahrzehnte hat sich die globale landwirtschaftliche Produktion nahezu verdreifacht. Dieser Produktionsanstieg ist einerseits mit der Ausbreitung landwirtschaftlicher Flächen, und andererseits mit der Intensivierung der Landwirtschaft zu erklären. Die Intensivierung der Landwirtschaft umfasst den Einsatz von ertragssicheren Sorten, Maschinen, Bewässerung, künstlicher Dünger und Pflanzenschutzmitteln. Sowohl die Intensivierung der Landwirtschaft, als auch die Ausbreitung von landwirtschaftlicher Fläche kann zu Umweltproblem und Beeinträchtigung menschlicher Gesundheit führen und trägt zum Klimawandel bei. Die Umstellung zu nachhaltiger Landwirtschaft ist daher eine der großen Herausforderungen des 21sten Jahrhunderts. Es ist zu erwarten, dass diese Herausforderung durch die wachsende Nachfrage für Agrarprodukte erschwert werden wird. Die wachsende Nachfrage wird von der wachsende, immer reicheren Bevölkerung, sowie der Produktion von Bioenergie zur Sicherstellung der Energiesicherheit oder als Klimaschutzmaßnahme, angetrieben. Die vorliegende Dissertation untersucht den Einfluss von Unsicherheiten in gesellschaftlichen Prozessen auf Landnutzungsänderungen in der Zukunft, unter Berücksichtigung von Bevölkerungswachstum, Ernährungspräferenzen, technischem Fortschritt, und Bioenergieproduktion. Die zukünftige Entwicklung gesellschaftlicher Prozesse und des Klimas wird durch Szenarien beschrieben, zum Beispiel den sogenannten „Shared Socio-economic Pathways“ (SSPs) und den „Representative Concentration Pathways“ (RCPs). Der Einfluss dieser Szenarien auf Landnutzung wird mit dem globalen Landnutzungsmodell, dem „Parsimonious Land Use Model“ (PLUM), untersucht. PLUM konnte die beobachten, globalen Landnutzungsveränderungen im Zeitraum 1991-2010 nachstellen. Weiter konnte in dieser Arbeit gezeigt werden, dass die modellierte globale Landnutzung stark von angenommenen Ertragswachstumsraten abhängt. Um sicherzustellen, dass modellierte Ernteerträge keine biophysikalischen Grenzen überschreiten, wurde in dieser Arbeit PLUM mit Erntedaten komplementiert. Diese Erntedaten wurden von einem globalen Vegetationsmodell simuliert, welches den Einfluss von Klimawandel auf Pflanzenwachstum berücksichtigt. Wenn Bioenergieproduktion als Klimaschutzmaßnahme nicht berücksichtigt wird, wurde die globale Ackerfläche in 2100 auf 970-2280 Mha geschätzt; die heutige Fläche ist ca. 1500 Mha. Unsicherheiten in Bezug auf die Interpretation von Szenarien vergrößern die modellierte Spannweite in der globalen Ackerfläche auf 890-2380 Mha (\pm eine Standardabweichung) in 2100 und sollten bei der Analysen von Konsequenzen von Landnutzungsänderungen berücksichtigt werden. Wenn Bioenergieproduktion als Triebkraft im Landnutzungssystem berücksichtigt wird, werden im Jahr 2100 voraussichtlich weitere 603-1115 Mha Ackerfläche benötigt. Die Ausbreitung von Ackerfläche in

natürliche Wälder oder Grasland, wie zum Beispiel für Szenarien mit starkem Bevölkerungswachstum und langsamen technischem Fortschritt oder mit sehr starker Bioenergieproduktion, führte zu einem Wandel der Landbiosphäre von einer Kohlenstoffsенке zu einer Kohlenstoffquelle. Um langfristige, unhaltbare Konsequenzen von Landnutzungsänderungen zu vermeiden, wurde in der Literatur vorgeschlagen die globale Ausbreitung von Ackerfläche auf maximal 15% der eisfreien Landfläche zu begrenzen. Es konnte in der vorliegenden Arbeit gezeigt werden, dass unter heutigen Voraussetzungen innerhalb dieser 15% die globale Ernährungssicherung und ein erheblicher Beitrag zum Klimaschutz von Bioenergie bis zum Jahr 2050 nicht geleistet werden kann. Die zukünftige Ernährungssicherung im regionalen oder lokalen Kontext könnte ebenfalls gefährdet sein, wie in dieser Arbeit für Länder in der Sahel Region in Afrika gezeigt wurde. Für vier von fünf Szenarien verursachte die stark ansteigende Nachfrage Engpässe in der Lebensmittelversorgung. Die Umsetzung von nachhaltigen Agrartechnologien sowie der Zugang zum Welthandel von allen Ländern werden in der Zukunft wichtige Themen zur Sicherstellung der Ernährungssicherheit sein. Insgesamt konnte die vorliegende Arbeit zeigen, dass Unsicherheiten in Bevölkerungswachstum, technologischem Fortschritt, Konsumtionsverhalten und Bodenverschlechterung einen großen Einfluss auf zukünftige Landnutzungsänderungen haben werden.

Sammanfattning

Den globala jordbruksproduktionen har de senaste fem decennierna nästan tredubblats. Produktionsökningen beror på ett allt intensivare jordbruk samt konvertering av naturliga ekosystem till jordbruksmark. Intensifieringen av jordbruket har skett genom ökad användning av högavkastande grödor, mekanisering, bevattning, konstgödsel och bekämpningsmedel. Både intensivare jordbruk och expansionen av jordbruksmark kan dock leda till miljöförstöring och risker för människors hälsa. Att ställa om till ett hållbart jordbruk samtidigt som efterfrågan på jordbruksprodukter och mark ökar, utgör en av 20:e århundradets stora utmaningar. Viktiga drivkrafter bakom ökad efterfråga är en växande befolkning, ekonomisk tillväxt men även ökad efterfråga på bioenergi. Bioenergiproduktion ses som en av många strategier för att minska utsläppen av växthusgaser. Klimatförändringar förväntas att ytterligare förstärka de utmaningar som samhället och inte minst jordbruket kommer att behöva tackla. I denna avhandling undersöks hur osäkerheterna i socioekonomiska processer och klimatförändringar kan komma att påverka framtida markanvändning. De socioekonomiska processerna omfattar till exempel befolkningsutveckling, förändrade mönster i kött- och mjölkkonsumtion, teknisk utveckling inom jordbrukssektorn och produktion av bioenergi. Framtida utveckling av socioekonomiska drivkrafter och klimatförändringar beskrivs av nya scenarier som används inom miljöforskningen, de så kallade "Shared Socio-economic Pathways" (SSP) och "Representative Concentration Pathways" (RCP). Förändringar i drivkrafter och deras effekter på markanvändningen studeras med en global markanvändningsmodell, "Parsimonious Land Use Model" (PLUM). PLUM, som på ett förenklat sätt representerar det globala jordbrukssystemet och kopplar till de bakomliggande drivkrafterna, visade sig kunna reproducera observerad global markanvändning på global skala för tidsperioden 1991-2010. Globala förändringar i jordbruksmark visade sig vara mycket känsliga för antaganden om teknisk utveckling inom jordbrukssektorn. I en efterföljande modellversion uppskattades därför den potentiella utvecklingen av spannmålsskördar med hjälp av en global dynamisk vegetationsmodell, som tar hänsyn till effekterna av klimatförändringarna på skörden. Genom simuleringar av scenarier med PLUM uppskattades den framtida jordbruksmarken ligga mellan 970-2280 Mha år 2100, jämfört med dagens 1500 Mha. Den stora spridningen kan förklaras av de olika antaganden om de bakomliggande drivkrafterna i de olika scenarierna. Spridningen är i linje med andra uppskattningar av framtida jordbruksmark som nyligen publicerades i en vetenskaplig artikel. Osäkerheterna relaterade till hur man tolkar socioekonomiska processer och drivkrafter ökade spridningen till 890-2380 Mha (\pm en standardavvikelse) år 2100. Det är därför viktigt att även ta hänsyn till osäkerheter relaterade till tolkning av ett scenario, liksom till osäkerheter som

uppstår genom användning av olika markanvändningsmodeller. Vidare, när bioenergi inkluderas som en strategi för att minska klimatförändringarna, ökar den uppskattade efterfrågan av jordbruksmark med 603-1115 Mha år 2100. Det finns dock stora osäkerheter kopplade till hur mycket mark som använts för bioenergi i framtiden, relaterad till skördar, bioenergiteknologier, och tillgång till jordbruksmark. Kontinuerlig expansion av jordbruksmark på bekostnad av naturliga ekosystem, vilket sker i scenarier med stark befolkningstillväxt och låg teknisk utveckling eller scenarier med en stor produktion av bioenergi, resulterade i att biosfären till och med kan skifta från att vara en kolsänka till att vara en kolkälla. För att undvika de långsiktigt ohållbara konsekvenserna av ökad markanvändning har det tidigare uppskattats att den globala åkermarken inte bör överskrida 15% av all isfri mark globalt. Denna avhandling visar att om åkermarken hålls inom denna gräns, så är det omöjligt att säkra livsmedelsförsörjningen år 2050 och samtidigt producera bioenergi som bidrar till en minskad klimatpåverkan, om man i stort bibehåller dagens befolknings-, inkomst- och konsumtionsutveckling. Livsmedelsförsörjning kommer att vara i riskzonen under framtida socioekonomisk utveckling i ett lokalt till regionalt sammanhang, vilket här demonstrerades för länderna i Sahelregionen i Afrika. För närvarande är efterfrågan på resurser ifrån vegetationen mindre än tillgången vilket gör att försörjningsbalansen i Sahel är positiv, men den visade sig bli negativ under de kommande decennierna för fyra av fem studerade scenarier. För att säkra framtida livsmedelsförsörjning är det viktigt att globalt implementera hållbara jordbruksmetoder samt att säkra tillgång till den globala marknaden för alla länder. Totalt sett så bidrar osäkerheter i befolkningsutvecklingen, den tekniska utvecklingen, konsumtionsmönster och omfattning av markförstöring till en mycket stor spridning av våra uppskattningar av framtida användning av jordbruksmark.

1. Introduction

1.1 Land & society

Terrestrial ecosystems provide multiple services to society, such as, food, fibre, fuel, fresh water resources, pollination, the storage of carbon soils and biomass and recreation (Metzger et al., 2006). Prior to the beginning of agriculture, hunters and gatherers lived off the plants and animals in their surrounding lands. Agro-technological developments strongly interact with societal development and society's impact on the environment. The invention of artificial nitrogen fixation (Haber Bosch process) in the 20th century, together with the use of herbicides, irrigation, high yielding crop varieties and agricultural machinery, enabled drastic yield and production increases. The resulting intensification of agricultural production contributed to meeting the increasing food demand of the growing population globally, but also led to amplified environmental degradation (Foley et al., 2011).

Population growth is the strongest driver of increasing food demands, but the shift towards diets rich in animal products has become increasingly important as a driver for land-use and land-cover change (LULCC) over the last two decades (Alexander et al., 2015). Increasing per capita consumption of animal products is strongly correlated with per capita income. For example, rapid economic growth in China has been correlated with the doubling of per capita meat consumption over a period of less than two decades (Smil, 2002). Economic growth spurs urbanisation, leading to a decrease in cooking time and the adoption of globalised lifestyles, all enhancing the global shift towards (currently) more meat-rich diets (Satterthwaite et al., 2010; Smil, 2002).

From the advent of agriculture (ca. 8000 years before present) until industrialisation (1850 AD) global agricultural area (cropland and pasture) expanded from 0.015-1.3%¹ to 9.0-20.7% of global land area (Kaplan et al., 2010; Klein Goldewijk et al., 2011). Up to about 1950, agricultural land area increased to almost 26% of total land area. Though agricultural land increased globally by

¹ The large difference in estimates for historical agricultural land use is due to different assumptions of per capita land use.

about another 10% until 2009, regional abandonment of cropland has also been observed (FAOSTAT, 2013). At the same time the intensity of land use and food production increased. For example, cropland alone increased by 30% between 1961 and 2009 (Kastner et al., 2012). This is reflected in the transformation of the agricultural system from one dominated by extensive grazing towards an intensified agricultural system with an increasing share of crops produced for livestock feed.

1.2 Consequences of agriculture and land-use change

The expansion and intensification of agriculture has far-reaching consequences for the biosphere, the atmosphere and the hydrosphere. In the biosphere, large scale deforestation has led to the loss of natural ecosystems and has contributed greatly to accelerated biodiversity loss during the last century. Current extinction rates are 100 to 1000 times larger compared with natural extinction rates (Rockström et al., 2009). Cropland expansion into naturally vegetated areas has also reduced the carbon stored in forests or savannahs and hampers the capacity to store carbon in terrestrial ecosystems in the future. However, it is not only the carbon stored in biomass that is heavily affected by LULCC; carbon stored in soils (soil organic carbon, SOC) is lost due to unsustainable farming practices and cropland degradation. SOC is important for agricultural productivity (Ontl and Schulte, 2012). Conventional agriculture leads to soil erosion rates much larger (up to 100 times) than natural formation of soils or soil erosion under natural vegetation (Montgomery, 2007). The type of future LULCC and intensity of land management will contribute to determining the strength of the carbon sink or source of the terrestrial biosphere.

Today, combined carbon emissions from agriculture, forestry and other land uses (AFOLU) contribute about 10% to total global CO₂ emissions (Canadell and Schulze, 2014). Taking into account other greenhouse gases (GHG), such as methane (CH₄) and nitrous oxides (N₂O), AFLOU contribute about 20% to the total anthropogenic GHG emissions in 2010 (Tubiello et al., 2015). The most prominent sources of methane emissions are the livestock (ruminants) sector and rice production, while nitrous oxide is mostly emitted in response to fertilisation.

Other environmental pollutants commonly emitted through agricultural activities include excess nitrogen, antibiotics and pesticides in waterways. The heavy use of antibiotics in livestock farming and the occurrence of antibiotics in the natural environment lead to the selection of antibiotic resistant bacteria, some of which are dangerous for humans (and livestock). Yearly, approximately 700 000 people die due to infections with antimicrobial resistant bacteria (O'Neill, 2016). Human

health, especially the health of farmers, is also at risk by the use of pesticides. Pesticide poisoning causes the premature death of an estimated 250 000 people each year (WHO, 2004). Excess nitrogen in rivers, lakes and oceans severely impact aquatic biomes, exemplified by the prevalence of dead-zones (hypoxia) in the Baltic Sea (Carstensen et al., 2014). Agriculture and LULCC also impact the hydrosphere via the wide-spread use of irrigation. This has led, and continues to lead to the salinization of soils, depletion of aquifers and changes of hydrological regimes, leading to long-term unsustainability of irrigation and agriculture (Foley et al., 2005; Wichelns and Oster, 2006).

In conclusion, the consequences of agriculture and LULCC on the atmosphere, biosphere, hydrosphere are multiple, severe and inter-twined. Transitioning towards sustainable agriculture, therefore, is one of the key environmental challenges of the 21st century.

1.3 The challenges for future land-use

The challenge of transitioning to sustainable agriculture is amplified by the increasing pressures on terrestrial ecosystems. Current demographic trends suggest that the global population will continue to grow to 9.7 ± 0.5 billion people until 2050 (UN, 2015). Without major disruptions in the world economy, continued economic growth is foreseen. Developing and emerging nations are currently on their way to adopt Western diets, which are typically high in animal products, sugars and vegetable fats and require more agricultural land compared to cereal and vegetable-based diets (Keyzer et al., 2005; Smil, 2002; Tilman and Clark, 2014). However, despite increasing average consumption, inequalities in food supply across and within countries remain (Alexandratos and Bruinsma, 2012). Both malnourishment and diseases related to obesity will be major challenges in the future (FAO/IFAD/WFP, 2015). Additionally, between 2000 and 2030, urbanisation and population growth are projected to lead to the loss of 1.6-3.3 Mha yr⁻¹ (approximately the size of Swaziland or Belgium) of prime agricultural land (Lambin and Meyfroidt, 2011).

Mitigating climate change to the 2°C target² requires drastically reduced GHG emissions and contributions from all sectors, including agriculture and LULCC (Wollenberg et al., 2016). As described in the previous section, AFOLU is currently responsible for more than 20% of total GHG emissions, or around 10-12 GtCO₂eq yr⁻¹ (Tubiello et al., 2015). In order to meet the 2°C target, emissions from AFOLU could be reduced by 5-9 GtCO₂eq yr⁻¹ by 2030 (27% of the

² 2°C target: Keep global average temperature rise below 2°C compared with pre-industrial levels.

mitigation needed across all sectors), if a range of strategies are combined (Wollenberg et al., 2016). These strategies could include afforestation projects and reduced LULCC, the replacement of fossil fuels with bioenergy, carbon capture and storage (CCS), reducing food waste, transitioning towards sustainable diets, improving livestock and cropland (including paddy rice) management and the use of perennial crops and improved management of SOC (Glover et al., 2010; Smith, 2013; Wollenberg et al., 2016).

However, enhanced bioenergy production, partly driven by climate change mitigation efforts, but also driven by energy security concerns, increases the demand for land further. Between 2000 and 2010, modern biofuel production at the global level increased more than six fold (IEA, 2011), mainly in the form of first generation biofuels. First generation biofuels are produced with conventional technologies from feedstock high in sugar, starch or oil. Second generation biofuels, based on lingo-cellulosic feedstock, are in the initial stages of commercial use, but are not expected to play a major role before 2030. Traditional bioenergy, i.e., the burning of biomass (wood and dung) at the household level for heating and cooking, is still the prevailing energy source in many developing countries and contributes with the largest share of today's total bioenergy use (van Ruijven et al., 2008).

Currently, the land use related to bioenergy production is only around 1% of global agricultural land area. However, up to half of the observed cropland expansion during the last decade can be attributed to the increase in modern bioenergy production (Alexander et al., 2015; Prieler et al., 2013). This trend is likely to continue with the ambitious energy policies of several nations, including the U.S. and Europe. For example, the EU targets 10% renewable energy in transport by 2020 (IEA, 2011), of which the main share is still expected to come from biofuels (EC, 2015). The consequences for LULCC, however, are very uncertain (projected from 230 to 3590 Mha in 2050), and depend on the variety and efficiency of processes in the bioenergy production, the yield of biomass sources, as well as climate change effects on yields (Berndes, 2003; Haberl et al., 2011; Heinimö and Junginger, 2009). Simultaneously, the provision of other ecosystem services, e.g. pollination, water purification and recreational areas need to be secured.

However, the implementation of the aforementioned strategies to mitigate climate change is dependent on other uncertain factors and drivers, such as the price of oil, the implementation of policies, consumer behaviour and climate change itself. In some regions yields might increase due to increasing temperature and the CO₂ fertilization effect (Haberl et al., 2011) whereas changes in precipitation patterns and more frequent extreme weather events (e.g., droughts and floods) are projected to decrease yields in other regions (Lobell and Field, 2007; Rosenzweig

et al., 2001). Global effects of climate change on agricultural productivity are thus uncertain.

Irrespective of the mean global impacts, climate change adaptation is important to ensure livelihood strategies especially for small-scale farmers. The role of management in agriculture is crucial to adapt to the adverse climate change effects (Lobell et al., 2008). Simpler techniques, such as adapting sowing dates and crop varieties have to be supplemented with more technologically advanced methods. These include, for example, the breeding of new crops and precision agriculture, as well as improved irrigation schemes (Lobell et al., 2008). Technological change can contribute to closing yield gaps and reduce post-harvest losses, but needs to be facilitated through investments and education (FAO, 2009; Hertel, 2015).

1.4 Research objectives

The objective of this thesis is to contribute to the understanding of the impacts of uncertainties in socio-economic drivers, such as dietary changes, bioenergy production and technological change, on future agricultural LULCC (Figure 1).

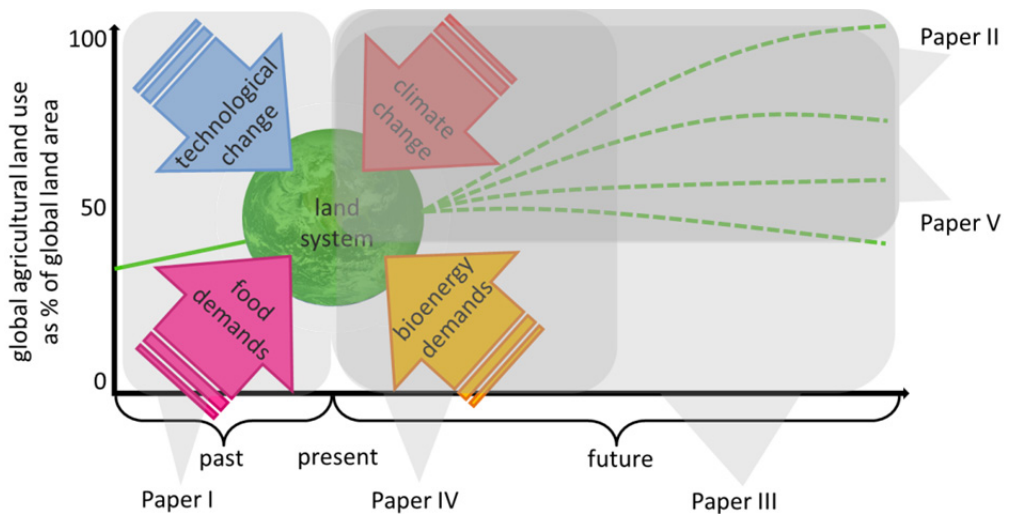


Figure 1: Overview of drivers (coloured arrows) on the land system (green circle). The green solid line represents the development of agricultural land use during the last decades. The green dashed lines indicate the possible development of agricultural land use in the future. The grey shaded areas indicate the timeframe and areas covered by the appended papers (Paper I – Paper V) in the thesis.

Specifically, the thesis aims to:

Develop, test, and apply a global parsimonious agricultural land-use model (Paper I-V).

Assess uncertainties and sensitivities of global cropland development in the past decades (Paper I).

Quantify cropland ranges for the new scenarios (Socio-economic Shared Pathways, SSPs and Representative Concentration Pathways, RCPs), by employing a conditional probabilistic framework (Paper II).

Estimate the direct and indirect effects of energy mitigation strategies on LULCC and the carbon balance of the terrestrial biosphere (Paper III).

Analyse potential pathways and trade-offs to reach food security in 2050 while at the same time producing bioenergy in order to meet the 2°C target (Paper IV).

Explore the consequences of changes in food demand and yield development under multiple socio-economic and climate scenarios in a regional context (Paper V).

2. Methods

Addressing the aforementioned challenges requires understanding of the coupled human-environment land system and its drivers. Qualitative and quantitative methods of land system science include monitoring of LULCC, land system modelling and analysis of future LULCC visions, as well as vulnerability, resilience and sustainability assessments (Rounsevell et al., 2012; Turner et al., 2007). Within this thesis the global Parsimonious Land Use Model (PLUM) was evaluated against historic data (Paper I) and applied to explore future agricultural LULCC (Paper II-V). Three different, complementary models were used to provide input to PLUM (Paper II-V) and to explore the consequences of PLUM output, i.e. simulated food demand and LULCC. Paper III explores the impact of LULCC on the carbon balance of the terrestrial biosphere and Paper V assesses the consequences of changing food demands on the balance of vegetation supply and demand in the Sahel region. An overview of the development of PLUM (Section 2.1.1) and application of the complementary models (Section 2.1.2) is presented below.

To run models into the future involves assumptions about the development of key drivers, such as population growth, economic growth, life-style and technology. A consistent and plausible set of assumptions is qualitatively described by scenario storylines that are then interpreted and quantified with model simulations, called scenario quantifications (Nakicenovic et al., 2000). A range of contrasting and complementing scenarios provides insights to plausible future developments of the land system. Scenarios are not to be understood as predictions of the future (Reilly and Willenbockel, 2010). Scenarios are helpful tools to assess impacts of uncertainties in socio-economic drivers on LULCC and to support decision-making. To quantify the impact of uncertainties in scenario assumptions for model outcome, conditional probabilistic scenarios were developed in Paper II (Section 2.2.1). Exploratory scenarios were used to study the impact of LULCC on the terrestrial carbon balance and regional vegetation demand-supply balance (Paper III and Paper V, Section 2.2.2). To explore how a set of desirable targets can be achieved in the future, a normative scenario approach was used in Paper IV (Section 2.2.3).

2.1 Developing, evaluating and applying models

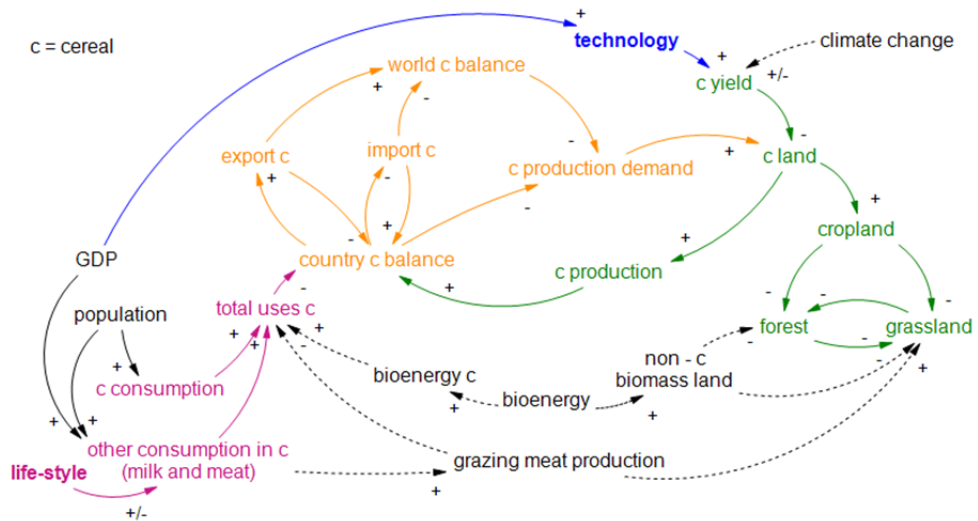
2.1.1 The Parsimonious Land-Use Model

Conceptualization, development and evaluation (Paper I)

All models are simplified representations of real-world observations and used to test and build our understanding of a system. Depending on the research question at hand, as well as the spatial and temporal scales covered with the modelling exercise, models need to consider different levels of complexity. The purpose of Paper I was to create a model where the underlying processes and drivers were reported and implemented in a transparent manner so that development of LULCC can be associated to changes in drivers (opposed to black-box models). At the same time the model should be able to reproduce observed agricultural LULCC at the global to country scale. To develop such a model a parsimonious approach (also known as Occam's razor), which favours the simplest explanation for the behaviour of a system, was used as a leading principle.

In the parsimonious conceptual model (Figure 2), agricultural land use change is driven by shifts in food demands and yield increase, which in turn is assumed to be driven by advances in technology (e.g., use of fertilisers, mechanisation and irrigation). Cereals are assumed to be a proxy for food and feed demand and changes in cereal land are used as proxy for changes in cropland. Simple demand and supply balances represent the trade flows between countries (Paper I).

The implementation of the conceptual model was based on a set of rules describing the functional relationships represented in Figure 2 to create the Parsimonious Land Use Model (PLUM). The model was implemented in the visual modelling environment Simile (Muetzelfeldt and Massheder, 2003). The model was initialised with data from the Food and Agriculture Organization Statistics (FAOSTAT, 2013) for the year 1990. The parameterisation of the model was based on a statistical analysis of FAOSTAT data from 1961-1990. The model was run for the time period 1991-2010, with continuous data input for population and Gross Domestic Product (GDP) from the World Bank database (WB, 2012).



To evaluate PLUM, simulations of agricultural LULCC were compared with data from FAOSTAT for 1991-2010. Parameter values for global models come with uncertainty as they cannot accommodate cross-country variability of input parameters. Thus, to assess the sensitivity of the model output to the uncertainty in the input parameters, a variance-based global sensitivity analysis (GSA) was performed (Lilburne and Tarantola, 2009; Saltelli et al., 2008; Paper I).

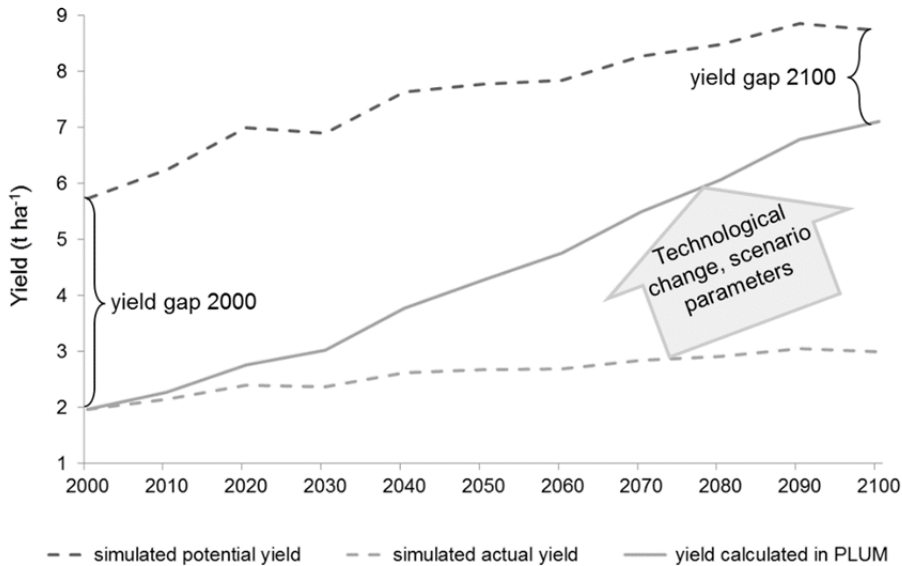


Figure 3: Decreasing yield gap for Ukraine. The scenario parameters related to technological change determine how rapidly the yield gap decreases over time (the arrow only being symbolic, indicating the drivers of changing yield gap).

Under the climate conditions forced with the RCP achieving a radiative forcing of 6 W m^{-2} by 2100 (RCP6.0; Masui et al., 2011) simulated carbon fertilisation has a strong effect on crop yields, e.g., for Ukraine potential yields are simulated to increase from below 6 t ha^{-1} to above 8 t ha^{-1} from 2000 to 2100 (dark grey dashed line, Figure 3). At the same time, the strong economic and technological change in SSP5 results in a tripling of yields during the period 2000-2100 (grey line, Figure 3) and thus a decrease in the yield gap for Ukraine.

In addition to the introduced biophysical boundary for yield growth, the area available for conversion to cropland was revised. Previously, it was assumed that all grassland and forest (natural vegetation, NV) could be converted to cropland. However, some areas covered by natural vegetation are not suitable for agriculture. Thus, in a first step, potential arable land as calculated by FAO (2000) was included in PLUM to restrict the maximum future cropland expansion. One additional scenario parameter was introduced to describe the level of conserved natural vegetation (ranging from 4-16% of total potential arable land in the different scenarios). In a subsequent model version (used in Paper III – Paper IV) the estimates of potential cropland from FAO (2000) were updated with estimates based on the Global Agro-ecological Zone database (FAO/IIASA, 2011).

Bioenergy from conventional energy crops (Paper III)

As outlined in the introduction, mitigation efforts and energy security concerns are likely to increase the demand for land for bioenergy production. Paper III aims at assessing the additional demand for cropland due to bioenergy production and its impact on the terrestrial carbon balance. Different assumptions regarding available resources for bioenergy production (industrial waste, forestry residues, agricultural by-products or dedicated energy crops) or available technologies (first generation, second generation biofuels, modern bioenergy), as well as uncertainties regarding yields and conversion efficiencies contribute to a wide range of bioenergy production and related LULCC estimates in the literature. However, for PLUM, only the production of bioenergy from conventional energy crops³ was considered (Paper III).

The production of energy crops in PLUM was assumed to predominantly occur on abandoned cropland, but if abandoned cropland is not available, the production of energy crops was assumed to expand into natural vegetation. Bioenergy production was assumed to be mainly produced in countries with large current bioenergy production, as well as countries with sufficient remaining natural vegetation (in cases where bioenergy cannot be produced on abandoned cropland).

Nutritional status (Paper IV)

Different socio-economic scenarios project varying degrees of increase in per capita food supply. To assess whether the simulated food supply is adequate in terms of dietary energy requirements (Paper IV), calculations of per country average nutritional status, indicated by daily food supply (kcal cap⁻¹ d⁻¹), were included in the model version used for Paper IV. It was assumed that the energy content of modelled food commodities (cereals, milk, meat) are constant and that a scaling factor can be used to adjust food supply included in PLUM (kilocalories from cereals, milk and meat consumption) to reported total food supply (kilocalories from all food items included in FAOSTAT). This scaling factor was applied during the entire simulation period. The scaling factor was only adjusted for countries with very large initial scaling factors, on the basis that if per capita meat consumption increases the scaling factor decreases (Paper IV).

³ Energy crops: “grown specifically for energy purposes, including sugar and starch feedstocks for ethanol (corn, sugarcane and sugar beet), vegetable-oil feedstocks for biodiesel (rapeseed, soybean and oil palm fruit) and lignocellulosic material (switchgrass, poplar and miscanthus)” (OECD/IEA, 2012).

2.1.2 Complementary models

LPJ-GUESS (Paper II, Paper III, Paper IV)

The global dynamic vegetation model LPJ-GUESS (Lindeskog et al., 2013; Smith, 2001) simulates the yields of 11 globally important crops, including wheat, maize and rice (Lindeskog et al., 2013). The model accounts for the effects of temperature, precipitation and atmospheric CO₂-concentrations on crop yields and the productivity of natural vegetation. Future yield simulations with LPJ-GUESS were performed with climate patterns derived from general circulation models (GCMs) and used as input to PLUM (see Section 2.1.2, Paper II-IV). LPJ-GUESS was also used to estimate the impact of LULCC and mitigation-induced reduced climate change on the carbon pool of the terrestrial biosphere (Paper III).

Climate-economy model (Paper III)

In Paper III the implications of mitigation strategies in the energy sector on LULCC are explored. One possible implication of mitigation strategies is the reduced impact of climate change on the global economy (indicated by Gross World Product, GWP) and hence increased consumption and investments in agricultural management with various impacts for LULCC. Further, bioenergy demand as well as climate-driven yield development are influenced by mitigation strategies and can have implications for future LULCC.

The damage on GWP, bioenergy demand and concentration pathways were quantified with the climate-economy model, which estimates the development of the global climate and economy in the future (Golosov et al., 2014). The consumption of three energy types (oil, coal and clean energy, including renewables and nuclear and excluded from carbon taxes) is determined by prices of, and taxes for, these different energy sources, respectively (see Paper III). Further, the climate-economy model estimates the damage on Gross World Product (GWP) per additional unit of carbon in the atmosphere, depending on the damage factor (Paper III). For the scenarios, mitigation strategies were implemented by assuming different levels of the optimal carbon tax (consistent with the challenge for mitigation, see Paper III). Carbon taxes are generally regarded as an effective economic incentive to reduce greenhouse gas emissions. The optimal carbon tax is proportional to GWP with a proportionality factor depending on the expected damage, the carbon duration in the atmosphere and the future discount rate (Golosov et al., 2014).

Biome-based Meta-model Ensemble (BME) and supply and demand balance in the Sahel region (Paper V)

With its fast run-time, PLUM can be used to explore consequences of changes in socio-economic drivers on LULCC very rapidly. Similarly, the use of a meta-model allows the direct assessment of changing climate conditions on annual vegetation growth (estimated with Net Primary Production, NPP). Thus, in Paper V NPP time-series (as indicator for crop yields) were simulated with the global Biome-based Meta-model Ensemble (BME; Paper V; Sallaba et al., 2015) and used as yield input to PLUM. The BME was developed based on process-based NPP simulations forced with different climate patterns in the global ecosystem model LPJ-GUESS (Smith et al., 2014). The biome definition in the BME includes 13 biomes, differentiated by soil moisture and soil temperature regimes (Reich and Eswaran, 2002).

To explore the impact of socio-economic and climate scenarios on future regional NPP supply and demand balances, the five SSPs in combination with the RCPs were used. The NPP supply and demand balance was calculated converting food demand simulated with PLUM into NPP demand (Abdi et al., 2014, Paper V). NPP supply was simulated using cropland projections of PLUM downscaled to grid cell level (0.5 degree) together with the BME NPP estimates. This facilitated the analysis at the local (grid-cell), country, and regional (Sahel) level.

2.2 Scenario analysis

2.2.1 Conditional probabilistic futures (Paper II)

Paper II assesses the deep uncertainties, i.e. not knowing the development of drivers, described by scenarios, as well as the uncertainties arising from scenario interpretation, using the conditional probabilistic approach. The conditional probabilistic approach combines exploratory scenarios with the probabilistic approach and is useful in exploring parameter uncertainty within and across scenarios (Brown et al., 2014; van Vuuren et al., 2008). The probabilistic approach acknowledges known uncertainties in a system and assigns probability distributions to parameters describing the system (van Vuuren et al., 2008). Exploratory scenarios assess the development of drivers described in the scenario storyline (Reilly and Willenbockel, 2010), but uncertainties related to interpretation of the storyline are not considered. In the conditional probabilistic approach, the assumptions and probability distributions for parameters describing the system are conditional for the underlying exploratory scenario.

In Paper II, the most recent set of scenarios for environmental and climate research, the Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs) were used as underlying exploratory scenarios (Ebi et al., 2014; Moss et al., 2010; O'Neill et al., in press; van Vuuren et al., 2014). The RCPs describe concentration pathways that achieve a radiative forcing of 2.6-8.5 W m⁻² in 2100, corresponding to a likely global average temperature increase of 0.3°C and 4.8°C by the end of the 21st century relative to the 1986-2005 global average temperatures (Collins et al., 2013). The Shared Socio-economic Assumptions (SPAs) complement the SSPs and RCPs (Ebi et al., 2014; Kriegler et al., 2014; O'Neill et al., in press; van Vuuren et al., 2014), but were not considered in Paper II.

The SSPs outline five plausible pathways that societal development could follow and are characterised by the development of elements, such as population, equity, economy, trade, lifestyle, policies, technology and energy intensity (O'Neill et al., in press; Figure 4). Due to their different key characteristics, the SSPs have varying challenges for mitigation and adaptation. For example the high energy demand in SSP5 “Taking the highway” and the slow technological change in SSP3 “A rocky road” contribute to a high challenge for mitigation (O'Neill et al., in press).

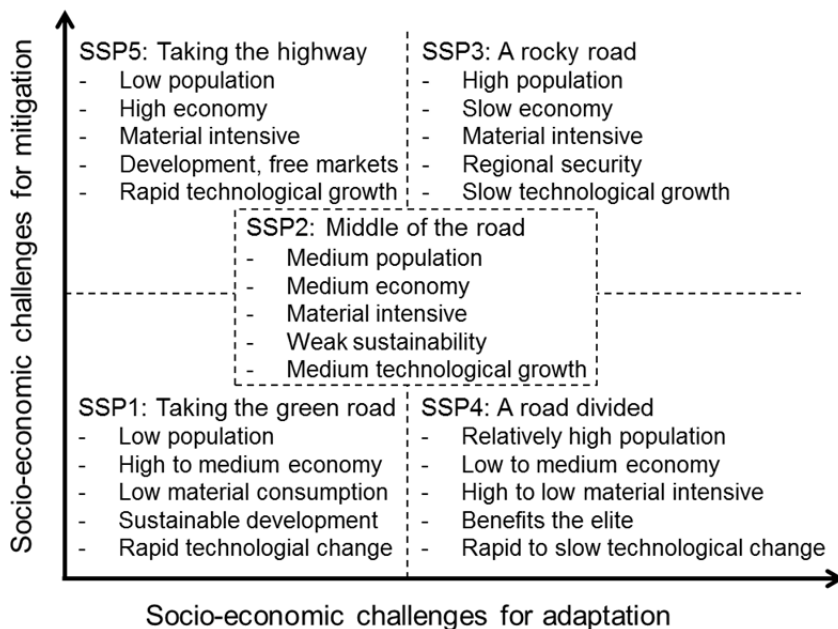


Figure 4: The SSPs in their “challenge space” for mitigation and adaptation (adapted from O'Neill et al. 2013) and their development in selected key elements: growth of population, growth of the economy, lifestyle, policy orientation and technological development (O'Neill et al., in press).

The SSPs do not take into account potential impacts of climate change or new climate policies and can thus be considered reference scenarios with respect to climate change (O'Neill et al., 2013).

In Paper II, conditional probabilistic futures (F1-F5) were developed (1-5 corresponds to SSP1-SSP5) which address the uncertainties that a given SSP would result in a given RCP, in addition to the previously mentioned uncertainties. The RCPs represent very stringent mitigation scenarios (RCP2.6) to very high emission scenarios (RCP8.5) and while in theory all SSPs and RCPs could be combined (van Vuuren et al., 2014), it is very implausible and unlikely that e.g. SSP5 with its heavy reliance on fossil fuels can achieve RCP2.6. In the SSP-RCP scenario matrix (see Paper II) probabilities for each RCP occurring conditional to the SSPs were specified. For example, the assumed probability for SSP1 to result in RCP2.6 is very low, while it is medium for RCP4.5 and RCP6.0 and non-existent for RCP8.5. For each SSP, the RCP-specific yield simulations from LPJ-GUESS were weighted through sampling from the quantified distributions in the SSP-RCP scenario matrix (Paper II).

2.2.2 Exploratory scenarios (Paper III and V)

To illustrate the impact of mitigation strategies on cropland (Paper III), as well as the consequences of changing demands for local to regional NPP balance in the Sahel (Paper V), exploratory scenarios were used. These exploratory scenarios were based on the SSPs (using the mean scenario values as described in Paper II), but uncertainties related to scenario interpretation and quantification were not considered in Paper III and V (opposed to Paper II).

The assumed mitigation strategies in Paper III include the introduction of a global carbon tax on fossil fuels (at levels consistent with each SSP's challenge for mitigation), as well as increased growth in efficiency for clean energies. The introduction of a global carbon tax reduces the use of fossil energies and increases the contribution of renewable energies to total energy demand. Thus, for Paper III the scenario-framework (previously exciting of five reference SSPs, SSPr1-5) was extended with five mitigation SSPs (SSPm1-5). The mitigation strategies for the mitigation SSPs were selected to be consistent with the challenge for mitigation and technological change of the underlying SSP. The projections of renewable energies from the climate-economy model were disaggregated for the different renewable energy sources based on their contribution in the energy scenarios of the OECD/IEA (2012). The bioenergy projections were then used as input to PLUM. Similarly, the emission pathways of the climate economy model were used to inform the scenario matrices (one for the reference scenarios and one for mitigation scenarios as the probabilities achieving a certain RCP change with

mitigation strategies). The damage of GWP was downscaled to country level and included in PLUM for Paper III. Paper V used the reference SSPs only.

2.2.3 Normative scenario approach (Paper IV)

In Paper IV, alternative futures that achieve food security in 2050, as well as staying within the planetary boundaries of global cropland and contribute to stringent mitigation efforts, were explored using the normative scenario approach. In the normative scenario approach, a set of desirable targets that the system should reach in the future is defined and realisations that fulfil these targets are developed. The normative scenario approach allows identifying robust strategies, i.e. common characteristics of realisations (or model parameterisations) which contribute greatly to achieving the normative targets.

For Paper IV, three normative targets were identified: a food-supply target (national average food supply by 2050 of minimum 2635 kcal cap⁻¹ d⁻¹), a cropland planetary boundary target (global cropland expansion to maximum 15% of total ice-free land area⁴ by 2050) and a bioenergy-mitigation target (contribution of energy crops with 9 EJ bioenergy in 2050 to stringent mitigation strategies). To identify parameterisations that achieve all three targets 120 000 PLUM runs were performed. These runs used business as usual population and economic development data and sampled values for selected scenario parameters from wide distributions, where the central value represented the observed current trend (2000-2012). For runs with enhanced bioenergy production (9 EJ from energy crops in 2050) yields driven by climate patterns derived with the stringent mitigation pathway RCP2.6 were used. For runs with business as usual bioenergy production (3 EJ from energy crops in 2050) yields driven by climate patterns derived with RCP6.0 were used.

⁴ The expansion of global cropland to a maximum of 15% of total ice-free land area was defined as planetary boundary for land use by Rockström et al. (2009). The planetary boundaries describe biophysical thresholds for the planet's subsystems or processes. Staying within the planetary boundaries gives humanity the possibility to live in a safe and stable environment (Rockström et al., 2009).

3. Results and discussion

3.1 Modelling and evaluating agricultural land-use change (Paper I)

The main objective of Paper I was to develop and implement a parsimonious model that reproduces past global agricultural LULCC and can be used to explore the impacts and uncertainties of changes in major drivers (e.g. population, economy and technological change) on agricultural LULCC. The parsimonious concept of PLUM coupled with the explicit treatment of uncertainties in model input parameters was shown to be sufficient to capture the observed trends in global time series of consumption, production, yield and agricultural land-use for the period 1991-2010 (Figure 5). The trends of globally increasing cereal, meat, and milk consumption are captured by the model, though the simulated ranges (Figure 5, \pm one standard deviation, green shaded area) only cover the variability in observed trends (Figure 5, black lines).

Other globally observed time series (Figure 5) are well captured by the model, except for the large interannual variability in cereal land during parts of the evaluation period. At the country level, cereal land changes were simulated at varying levels of agreement with observed data from 1991-2010. For large cereal producers such as India, China and the US, simulated changes in cereal land were similar to the observed changes in cereal land during 1991-2010. However, PLUM only projected a slight decrease in cereal land during 1991-2010 for Russia, while in reality the large structural changes in the agricultural system succeeding the end of the Soviet Union era led to wide-spread abandonment of cereal land in Russia.

The global sensitivity analysis showed the importance of technological change for increases in yield development, especially in developing countries. Currently achieved yields in developing countries are often very low and have large potential to decrease the yield gap, i.e. the difference between potential and actual yield (Licker et al., 2010). The role of increases in yields for developing countries in meeting (future) food demand has been demonstrated by others (Balmford et al., 2005; Fischer et al., 2009; Foley et al., 2011).

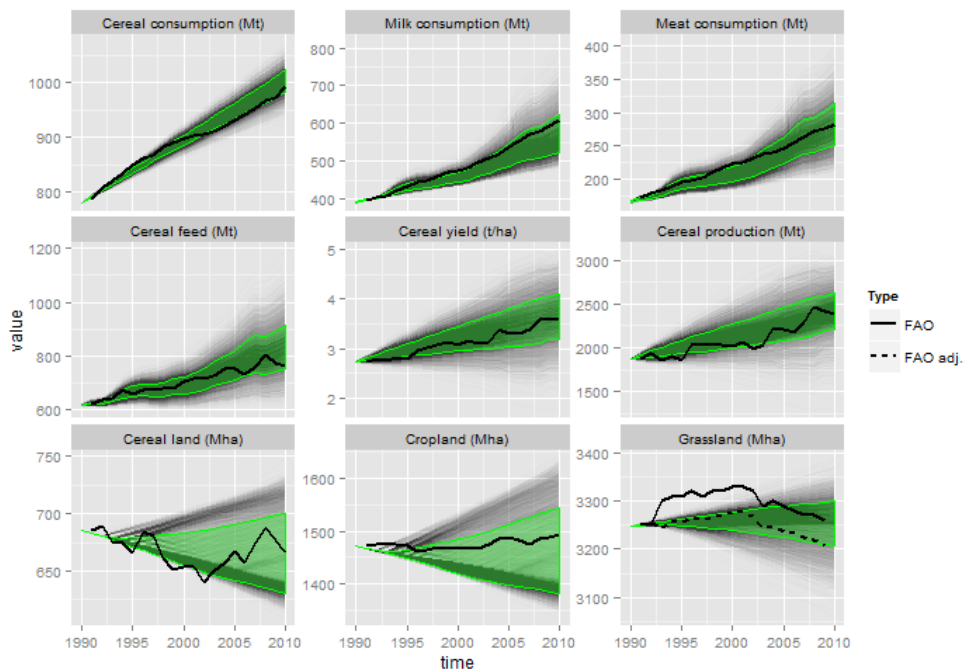


Figure 5: Model runs (faint gray lines) and standard deviation (green shaded area) for global consumption (cereal, milk, meat, Mt), global cereal feed (Mt), global average cereal yield (t ha^{-1}), cereal production (Mt), cereal land (Mha), cropland (Mha) and grassland (Mha). Global observed time-series (FAOSTAT) are indicated with black lines. For grassland an adjusted time series (subtracted data reporting inconsistency for Saudi Arabia between 1992 and 1993) is indicated using a black dashed line.

The considerable uncertainty of yield development points also at the potential to improve the implementation of yield representation in PLUM. Part of the uncertainty in the yield development, especially at the high end of projections, arises as PLUM at this stage does not include biophysical limitations to yield increase.

When PLUM is applied for future simulations, the assessment of the assumptions underlying PLUM is important, i.e. cereals as a proxy for food demand and cereal land as proxy for cropland changes or the simplified trade mechanism. This assessment can be facilitated by the transparent reporting of underlying assumptions and model documentation in Paper I. Another advantage of the relative simplicity of PLUM is its rapid run-time, allowing otherwise expensive sensitivity experiments and the exploration of uncertainties in input parameters. Overall, the generalised representations of socio-economic processes were shown to be sufficient to replicate global agricultural LULCC and provide a new modeling approach that is suitable for different types of scenario assessments.

3.2 Assessing uncertainties of future global cropland change (Paper II)

Paper II aims at providing scenario quantifications of cropland for 2000-2100 (combining SSPs and RCPs) and to assess uncertainties due to scenario interpretation. Quantifying the effect of deep uncertainties represented by the socio-economic scenarios (and underlying the cropland futures F1-F5) on future LULCC results in a range of 970-2280 Mha for future cropland by 2100 (Figure 6, solid lines). The here simulated cropland range is slightly lower than the preliminary cropland estimates of 1430-2810 Mha cropland by 2100 for the five SSPs (SSP-Database, 2015), but is within the range of simulated cropland (930-2670 Mha by 2100) presented in recent model inter-comparison studies (Alexander et al., 2016; Prestele et al., 2016). The lower end of the here projected range is simulated for F1 and can be related to low population growth, as well as environmentally conscious behaviour and subsequently relatively low levels of consumption of animal products in this scenario. Further, strong technological change in this scenario contributes to a strong simulated increase in global average yield, from 3.1 t ha^{-1} in 2000 to $5.4 \pm 0.5 \text{ t ha}^{-1}$ in 2100 (Paper II).

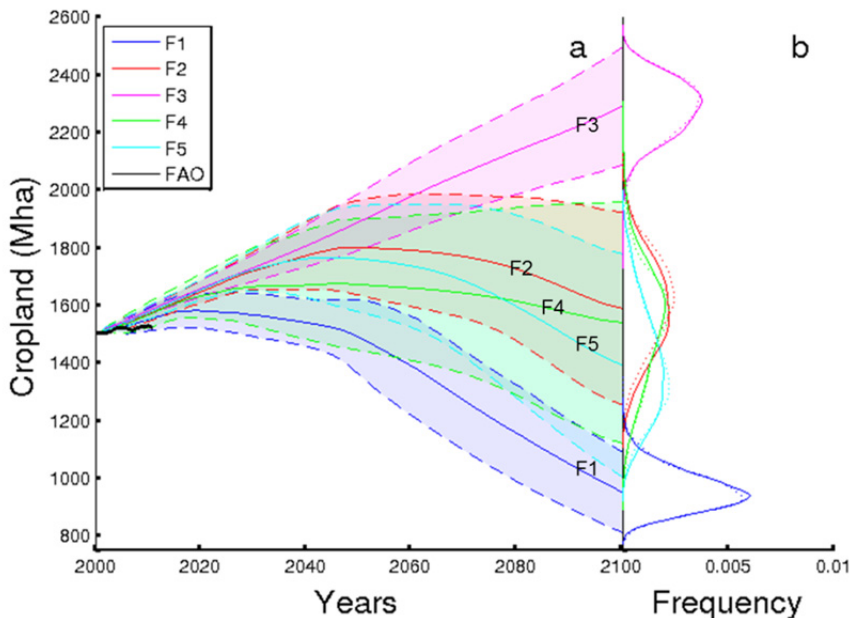


Figure 6: Panel a: cropland development from 2000 to 2100 for the five cropland futures F1-F5 (solid line: mean, range with dashed lines: ± 2 standard deviations). Panel b: Probability density functions fitted to all runs for each scenario in 2100, solid lines are runs with sampling yield variations due to GCM patterns and the scenario matrix and dashed lines are runs where the mean yield was used.

Increasing global average yield is critically dependent on implementation of current management practices and investments in infrastructure especially in developing countries as shown in Paper I, which is emphasised in F1 due to high equity and distribution of technologies. Yield developments in the simulations for Paper II are constrained by biophysical processes implemented in the global vegetation model. Compared to other global crop models the simulated potential yields are at the higher end of estimates (Rosenzweig et al., 2014).

By contrast to F1, F3 is characterised by strong population growth (12.1 billion people in 2100), a resource-intensive lifestyle, as well as low technological change. The combination of the directions of these drivers results in continuous global cropland growth, reaching 2280 Mha in 2100. The three other scenarios, F2, F4 and F5, show similar, medium cropland development due to balancing dynamics of drivers like population growth, shifts in diets, and technological change. The uncertainties in scenario interpretation lead to strongly overlapping ranges of cropland in 2100 for especially F2, F4 and F5, and even some overlap with F1 (Figure 6, \pm two standard deviations, ranges with dashed lines).

In a different analysis, which was part of a model inter-comparison exercise (Alexander et al., 2016), PLUM simulated cropland changes that are located in the middle of the range spanned by several LULCC models. In this case the cropland changes were simulated for the SRES (Special Emission Report Scenarios). The wide range of simulated LULCC is not only due to uncertainties in drivers represented in the scenarios, but also due to model uncertainty. Model uncertainty arises through incomplete understanding of the system represented in a model, as well as different implementations or selections of process to include in a model.

Paper II showed that considering the uncertainties in scenario inputs (i.e., time-series such as population, economic income and yield, as well as model parameters) is equally important as acknowledging deep uncertainties and model uncertainty. Further Paper II provided a streamlined set of quantifications of LULCC for the new scenarios of environmental change applying a novel SSP-RCP scenario matrix.

3.3 Impact of energy mitigation strategies on global land use and terrestrial carbon balance (Paper III)

Paper III aimed at exploring the impact of mitigation strategies in the energy sector on global LULCC. One further objective of Paper III was to explore the consequences of future LULCC for the carbon balance of the terrestrial biosphere. The introduction of mitigation strategies, mainly implemented by applying scenario-consistent levels of a global carbon tax, was found to be very effective in decreasing the future use of fossil fuels and consequently atmospheric carbon. The high damage factor and thus high anticipated damages due to climate change in combination with strong mitigation strategies in SSP4 were especially effective, reducing atmospheric carbon from levels comparable with RCP6.0 in the reference scenario to RCP2.6 in the mitigation scenario. The mitigation-induced reduction in climate change had varying impacts on global average yields (Figure 7, panel a, yellow bars). Generally, the impact of increased bioenergy production in the mitigation scenarios (Figure 7, panel b, blue bars) contributed predominantly to the difference in global cropland area between the mitigation and reference scenarios. For SSP1, SSP2, SSP3 and SSP4 global cropland expansion from 2000-2100 was 12%, 42%, 19% and 54% respectively larger in the mitigation scenarios compared to the reference scenarios. The simulated increase in cropland area for bioenergy production in the mitigation scenarios in Paper III (from 54 Mha in 2000 to 603-1115 Mha by 2100 for SSP1-SSP4) compares to 230-3590 Mha simulated bioenergy driven LULCC by a range of models and studies summarised in Haberl et al. (2010).

Simulated global cropland was observed to continuously expand for SSP2 mitigation and SSP4 mitigation, as well as SSP3 reference and mitigation (see Paper III). The strong cropland changes in SSP3 arriving at around 4000 Mha by 2100 are not solely driven by bioenergy production (430 and 730 Mha cropland for bioenergy in reference and mitigation scenario in 2100), but also strongly driven by population growth, resource-intensive lifestyles as well as low technological change. However, even if bioenergy would be not considered, the simulated cropland changes in Paper III for SSP3 are considerably larger than in Paper II (2180-2380 Mha in 2100). There are three main reasons for this difference, two related to conceptual uncertainties and one related to interaction effects for simulated yields, as described below.

In Paper II, in SSP3 demand was not actually met, potentially leading to food insecurity.

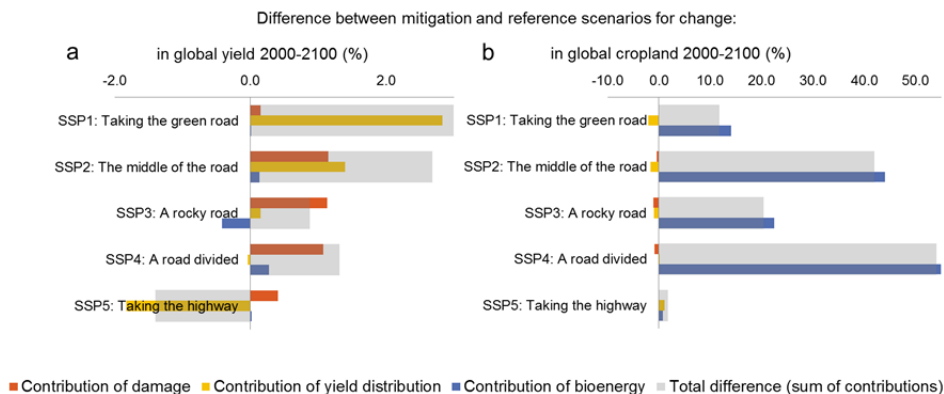


Figure 7: Differences between reference and mitigation scenarios for changes in global yield (2000-2100, %, panel a) and changes in global cropland (2000-2100, %, panel b). The grey bar indicates the total differences (sum of differences due to impacts of changes in damage, yield distribution and bioenergy), while the coloured bars show the contribution of different impacts to the total difference.

Conceptually it is difficult to know how trade would contribute to a global underproduction in a regionalised scenario such as SSP3. However, consistent with the main assumption of free global trade, in Paper III it was assumed that exporting countries would increase their production more rapidly if needed and thus demand was always fulfilled. The second conceptual change in Paper III was that PLUM simulated the intensification of the life-stock sector and thereby increased total cereal demand. Higher, and actually fulfilled demand, was combined with lower simulated average global yields in Paper III (3.2 t ha^{-1} in 2100) compared to Paper II (4.1 t ha^{-1} in 2100), leading to the larger simulated cropland expansion in Paper III. In Paper III, the distribution of RCPs conditional to SSP3 (based on simulation of concentration pathways with the climate-economy model) is very much centred around RCP6.0, while in Paper II the distribution (based on expert judgement) is wider, with larger influence of both RCP4.5 and RCP2.6. The difference in climate-driven yield time-series as input to PLUM accounted for 0.4 t ha^{-1} of the difference, while the remaining difference of 0.5 t ha^{-1} is due to expansion into less productive land, as well as climate-change induced damage on economic growth and reduced investments in agricultural management in Paper III.

Overall, the expansion of cropland into natural vegetation leads to losses of terrestrial carbon (Pugh et al., 2015; Shevliakova et al., 2009). The simulated LULCC in Paper III decreased the carbon pool in the terrestrial biosphere for all scenarios, but this effect was countered by increased uptake of carbon in the biosphere due to climate change driven CO_2 fertilization and longer growing seasons (Ahlström et al., 2012; Schimel et al., 2015), especially for scenarios with simulated strong climate change, such as SSP5 and SSP2 reference (Figure 8).

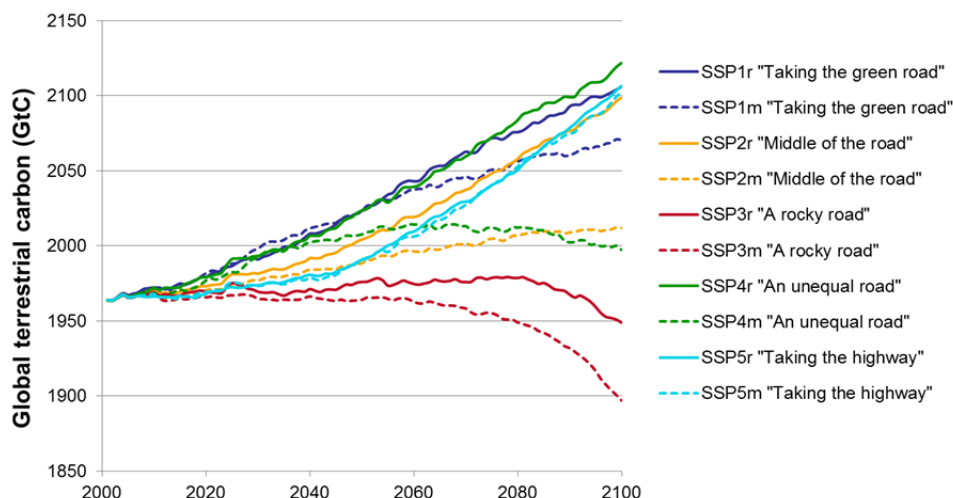


Figure 8: Changes in global terrestrial biosphere carbon pool (GtC) from 2000 to 2100 for all SSPs, reference (r) and mitigation (m) case. The slope indicates whether the net ecosystem carbon balance (NECB) is a carbon source (negative slope) or carbon sink (positive slope).

However, the loss of carbon due to the extreme cropland expansion in SSP3 was too large to be buffered by other effects, and led to a simulated net decrease of carbon in the biosphere (Figure 8, red lines). Even for SSP4 mitigation (Figure 8, green dashed line) the terrestrial biosphere becomes a carbon sink in the second half of the 21st century. For SSP3, the larger loss in SSP mitigation compared to SSP reference is due to decreased carbon uptake due to mitigation-induced reduced climate change. However, uncertainties in simulations due to model uncertainty in GCMs are larger than the difference simulated with the different RCPs (Ahlström et al., 2013) and should be acknowledged. Paper III demonstrated how cropland area could expand under mitigation through a global carbon tax on fossil fuels. Furthermore, Paper III showed that extreme cropland expansion could turn the terrestrial biosphere from a carbon sink into a carbon source.

3.4 Food supply and bioenergy production within the planetary boundary of global cropland (Paper IV)

Paper IV aims at identifying parameterisations that can achieve food security within the planetary boundary of global cropland change while also contributing to climate change mitigation. Providing adequate food supply for the total population in 2050 under current socio-economic trends (i.e. medium population and economic growth, continued shift towards diets rich in animal-products) within the

cropland planetary boundary (2010 Mha, indicated by the black dashed line in Figure 9) was shown to be only possible with 12 of the 120 000 simulations (Figure 9, yellow lines). These simulations commonly have strong yield increases, from 3.1 t ha^{-1} in 2000 to $4.9\text{--}5.2 \text{ t ha}^{-1}$ in 2050. The Food-Cropland parameterisation with high levels of conservation of natural vegetation at country-level (FC-highNV) has the strongest simulated yield increase, which can only be achieved with the rapid expansion of high-productive agricultural management strategies.

The strong intensification in FC-highNV could have large negative environmental consequences, such as water degradation, increased energy use and widespread pollution (Foley et al., 2011). However, the slightly stronger yield growth in FC-highNV compared to the Food-Cropland parameterisation low levels of conservation of natural vegetation at country-level (FC-lowNV) enables the protection of natural vegetation in all countries. Protecting ecosystems is important for biodiversity and related ecosystem services (Phalan et al., 2011).

The simulations suggested that within the cropland planetary boundary it is not possible to meet the food demand and to produce bioenergy that contributes considerably to climate change mitigation by 2050. However, considerable uncertainties with respect to the formulation of the bioenergy target exist.

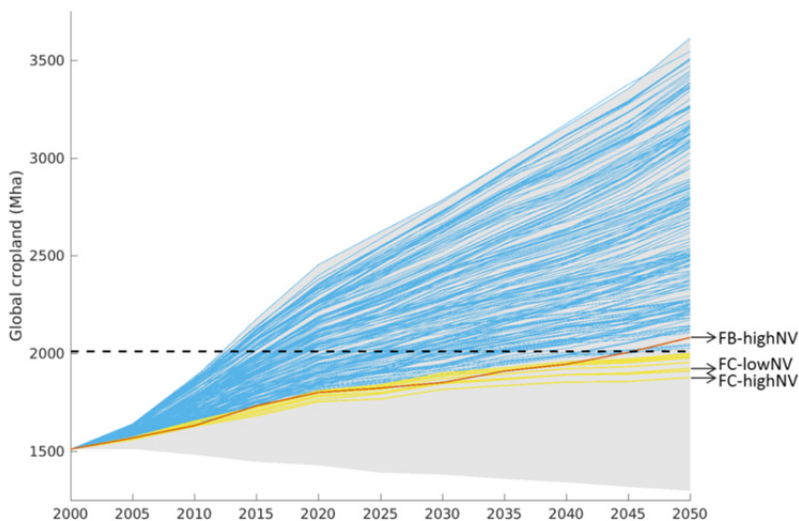


Figure 9: Global cropland for runs that meet the food-supply target (blue lines), runs that additionally also are below the planetary boundary for cropland (yellow lines, planetary boundary for cropland illustrated by the black dashed line). The red line indicates the run that achieves the food-supply and bioenergy-mitigation target, but is not within the cropland planetary boundary (Food-Bioenergy-highNaturalVegetation, FB-highNV). The grey shaded area indicates the range spanned by all runs.

In Paper IV it was assumed that first generation energy crops would contribute with 9EJ to the total bioenergy of 125 EJ by 2050. For example, an assumed smaller contribution of first generation energy crops on total bioenergy production would have reduced simulated cropland for bioenergy production.

Systematic changes, such as the large-scale transition towards less resource-intensive diets (e.g. substitution of meat and milk with vegetable protein sources, not implemented in PLUM) or decreasing food waste are desirable alternative strategies to meet the normative targets, but require well-implemented policies and a willingness in societies to change behaviour. Paper IV showed that producing bioenergy that contributes significantly to climate change mitigation, as well as ensuring food security within the planetary boundary of global land-use change is not possible under current socio-economic trends.

3.5 Supply and demand balances in Sahel for climate and socio-economic pathways (Paper V)

The objectives in Paper V were to study the impact of socio-economic and climate change on the supply and demand balance of vegetation in the Sahel region. For the majority of the simulated scenarios, NPP demand outstrips regional NPP supply from the second half of the 21st century (Figure 10, indicated by yellow to red colours). The SSP4 scenarios are the only scenarios where demand can be met with regional NPP supply throughout the simulation period. However, it needs to be kept in mind that the simulated demand does not necessarily meet the food requirements that would be sufficient to improve food security. Achieving food security requires, next to sufficient food supply, the distribution of, and access to food, by all people (Pinstrup-Andersen, 2009). For SSP4, a scenario characterised by high inter-country and within countries inequalities, as well as low economic growth for low income countries (LICs), food security does not improve for the majority of the population in the Sahel throughout the simulated period.

According to the modelling exercise, the earliest regional NPP shortfall occurs at the beginning of the 2030s for SSP5-RCP4.5. In this scenario strong economic growth coupled with the transition towards resource-intensive diets within the entire population, is combined with relatively low climate forcing and thus slightly lower yield improvements, compared with high emission pathways (RCP6.0 and RCP8.5). The impacts of the different climate scenarios (RCP4.5-RCP8.5) on vegetation growth explain the simulated range of shortages of 90 to 230 Tg dry-weight yr⁻¹ for the SSP2-RCP scenarios by 2050.

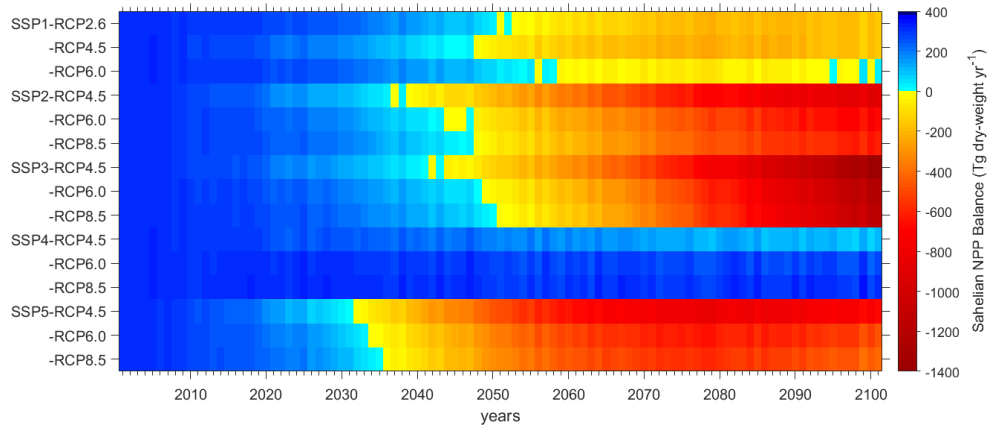


Figure 10: The NPP supply and demand balance for the entire Sahel region over the simulated time period. Blue colours visualise a positive NPP balance, while yellow to red colours indicate a negative NPP balance, also called NPP shortage. All SSP-RCP combinations with likelihoods >0.05 are displayed and grouped firstly according to SSPs and secondly to RCPs.

Generally, scenarios can be divided into two groups. Scenarios in the first group are characterised by peaking and declining population development, moderate to strong increases in consumption, as well as strong technological change and thus strong yield increase (SSP1 and SSP5 scenarios). These scenarios show an increase in NPP shortage at first, but thereafter a slight decline in NPP shortage during the last decade of the simulation period. By contrast, for scenarios with stronger population growth (SSP2 and SSP4, compared to SSP1 and SSP5), NPP shortages continuously increase throughout the simulation period (second group).

The importance of increasing yields, particular in developing countries with low initial yields, was emphasised by previous studies (Verburg et al., 2013) and is confirmed by the results here. Additionally, as the food supply in the Sahel region cannot be met in scenarios with increasing per capita food consumption, the role of trade with countries outside of the Sahel region will have to become more important in the future. However, increasing global trade will be challenging for scenarios such as the regionalised SSP3 and considerable risks for food security exists in these scenarios. Paper V demonstrated how different socio-economic development as well as different climate scenarios affect the balance of vegetation supply and demand in the Sahel region within the next decades.

4. Conclusion and outlook

The main objectives of the thesis were to develop a parsimonious model that could reproduce global agricultural change and to assess uncertainties in future LULCC applying scenarios and the developed model. PLUM successfully replicates observed changes of consumption, production and agricultural land-use at the global scale, but is limited with respect to country-level reproduction of observations. Incorporating biophysical limitations to yield growth into the socio-economic land-use model was important in order to increase confidence and decrease uncertainties in projected yield growth. Nevertheless, the simulations of future cropland area are still crucially dependent on how global yields respond to technological change. Different assumptions for the development of technological change across the scenarios contribute the most to the wide range of yield projections. The comparison of global average yield simulated in Paper II and Paper III showed that uncertainty related to the level of materialising climate change also contributes to the uncertainties in global average crop yield projections. By contrast, the impacts of spatial variability in climate patterns (due to different characteristics of the GCMs) on yield projections were found to be comparatively small.

Generally, uncertainties in the relationship of technological change and yield development contribute the most to uncertainties in the simulated cropland changes. Other important sources of uncertainties are population development, consumption patterns and land degradation. Without systematic changes in population as well as economic and dietary developments, ensuring world-wide adequate food supply without transgressing the global planetary boundary of land use change will require continued yield growth. The importance of increasing yields particularly in developing countries was highlighted by Paper I, Paper IV and Paper V. Additionally, the assessment of regional supply and demand in the Sahel showed that next to yield increases, all countries will need to participate in global trade in order to meet future food supply in resource-intensive scenarios.

Accounting for deep uncertainties represented by socio-economic scenarios and uncertainties arising from scenario interpretation results in a wide range of simulated cropland area. However, the uncertainty arising from process representation in PLUM has been shown to be important as well. For instance, fully considered global trade within a regionalised scenario was shown to result in

considerable higher cropland projections compared to a regionalised scenario where global trade is restricted. However, the simulations that lead to considerably higher cropland expansion also consider bioenergy production as an additional driver of LULCC, which forced cropland expansion into areas of lower productive potential (indirect LULCC). Simulations of extreme cropland expansion, driven by high population growth, high resource-intensity, low technological change and high bioenergy demand, can potentially turn the terrestrial carbon pool from a carbon sink into a carbon source. This would accelerate climate change considerably, as the terrestrial biosphere currently removes approximately 30% of the anthropogenic CO₂ emissions from the atmosphere.

In order to quantify impacts of LULCC on other aspects of the environment, e.g. atmospheric and aquatic pollution, further model development should be carried out in future research. This should include the representation of the demand for grassland from livestock farming, as well as the implementation of a larger variety of food commodities and bioenergy feedstocks. These model improvements would allow for a more dynamic simulation of grassland (as opposed to the current residual treatment of grassland) and allow for the projection of alternative and potentially more sustainable and healthy food supply patterns and more diversified bioenergy potentials.

Despite the suggested possible areas of model development it is important to keep the purpose of the here presented modelling approach in mind, which was to develop a parsimonious model. The model should be able to reproduce past global agricultural LULCC and to explore the impacts and uncertainties of changes in major drivers. While increasing model complexity might be useful to find a larger number of alternative pathways to future cropland, the model in its current state is well-suited to explore and communicate the uncertainties in underlying key drivers and processes of the land system for future land use outcomes.

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References

- Abdi, A.M., Seaquist, J., Tenenbaum, D.E., Eklundh, L., Ardö, J. (2014) The supply and demand of net primary production in the Sahel. *Environmental Research Letters* 9, 094003.
- Ahlström, A., Schurgers, G., Arneth, A., Smith, B. (2012) Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections. *Environmental Research Letters* 7, 044008.
- Ahlström, A., Smith, B., Lindström, J., Rummukainen, M., Uvo, C.B. (2013) GCM characteristics explain the majority of uncertainty in projected 21st century terrestrial ecosystem carbon balance. *Biogeosciences* 10, 1517-1528.
- Alexander, P., Prestele, R., Verburg, P.H., Arneth, A., Baranzelli, C., Batista e Silva, F., Brown, C., Butler, A., Calvin, K., Dendoncker, N., Doelman, J.C., Dunford, R., Engström, K., Eitelberg, D., Fujimori, S., Harrison, P.A., Hasegawa, T., Havlik, P., Holzhauser, S., Humpenöder, F., Jacobs-Crisioni, C., Jain, A.K., Krisztin, T., Kyle, P., Laval, C., Lenton, T., Liu, J., Meiyappan, P., Popp, A., Powell, T., Sands, R.D., Schaldach, R., Stehfest, E., Steinbuks, J., Tabeau, A., van Meijl, H., Wise, M.A., Rounsevell, M.D.A. (2016) Assessing uncertainties in land cover projections. Accepted for publication in *Global Change Biology*.
- Alexander, P., Rounsevell, M.D.A., Dislich, C., Dodson, J.R., Engström, K., Moran, D. (2015) Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. *Global Environmental Change* 35, 138-147.
- Alexandratos, N., Bruinsma, J. (2012) World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO.
- Balmford, A., Green, R.E., Scharlemann, J.P.W. (2005) Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Global Change Biology* 11, 1594-1605.
- Berndes, G. (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy* 25, 1-28.
- Brown, C., Brown, E., Murray-Rust, D., Cojocaru, G., Savin, C., Rounsevell, M. (2014) Analysing uncertainties in climate change impact assessment across sectors and scenarios. *Climatic Change* 128, 293-306.
- Canadell, J.G., Schulze, E.D. (2014) Global potential of biospheric carbon management for climate mitigation. *Nature Communications* 5, 5282.
- Carstensen, J., Andersen, J.H., Gustafsson, B.G., Conley, D.J. (2014) Deoxygenation of the Baltic Sea during the last century. *PNAS* 111, 5628-5633.
- Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J.,

- Wehner, M. (2013) Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Ebi, K.L., Hallegatte, S., Kram, T., Arnell, N.W., Carter, T.R., Edmonds, J., Kriegler, E., Mathur, R., O'Neill, B.C., Riahi, K., Winkler, H., Van Vuuren, D.P., Zwickel, T. (2014) A new scenario framework for climate change research: background, process, and future directions. *Climatic Change* 122, 363-372.
- EC (2015) Renewable energy progress report by the European Commission (EC), Brussels, Belgium.
- FAO (2000) World Soil Resources Reports: Land resource potential and constraints at regional and country levels. Rome, Italy.
- FAO, (2009) The technology challenge, High Level Expert Forum - How to Feed the World 2050, Rome, Italy.
- FAO/IFAD/WFP, (2015) The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress. FAO, Rome, Italy.
- FAO/IIASA (2011) Global Agro-ecological Zones (GAEZ v3.0). FAO, Rome, Italy and IIASA, Laxenburg, Austria.
- FAOSTAT, (2013) Statistic division of FAO, Production and Food Balance data. <http://faostat.fao.org/>, last access: 2013-09-25.
- Fischer, R.A., Byerlee, D., Edmeades, G.O., (2009) Can technology deliver on the yield challenge to 2050?, Expert Meeting on how to feed the world in 2050, Rome June 2009.
- Foley, J.A., DeFries, R.S., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K. (2005) Global Consequences of Land Use. *Science* 309, 570-574.
- 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., Zaks, D.P.M. (2011) Solutions for a cultivated planet. *Nature* 478, 337-342.
- Glover, J.D., Reganold, J.P., Bell, L.W., Borevitz, J., Brummer, E.C., Buckler, E.S., Cox, C.M., Cox, T.S., Crews, T.E., Culman, S.W., DeHaan, L.R., Eriksson, D., Gill, B.S., Holland, J., Hu, F., Hulke, B.S., Ibrahim, A.M.H., Jackson, W., Jones, S.S., Murray, S.C., Paterson, A.H., Ploschuk, E., Sacks, E.J., Snapp, S., Tao, D., Van Tassel, D.L., Wade, L.J., Wyse, D.L., Xu, Y. (2010) Increased Food and Ecosystem Security via Perennial Grains. *Science* 328, 1638-1639.
- Golosov, M., Hassler, J., Krusell, P., Tsyvinski, A. (2014) Optimal Taxes on Fossil Fuel in General Equilibrium. *Econometrica* 82, 41-88.

- Haberl, H., Beringer, T., Bhattacharya, S.C., Erb, K.-H., Hoogwijk, M. (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints. *Current Opinion in Environmental Sustainability* 2, 394-403.
- Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., Plutzer, C., Steinberger, J.K. (2011) Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy* 35, 4753-4769.
- Heinimö, J., Junginger, M. (2009) Production and trading of biomass for energy – An overview of the global status. *Biomass and Bioenergy* 33, 1310-1320.
- Hertel, T.W. (2015) The challenges of sustainably feeding a growing planet. *Food Security*.
- IEA, (2011) Technology Roadmap: Biofuels for Transport. International Energy Agency (IEA), Paris.
- Kaplan, J.O., Krumhardt, K.M., Ellis, E.C., Ruddiman, W.F., Lemmen, C., Goldewijk, K.K. (2010) Holocene carbon emissions as a result of anthropogenic land cover change. *The Holocene* 21, 775-791.
- Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S. (2012) Global changes in diets and the consequences for land requirements for food. *Proceedings of the National Academy of Sciences* 109, 6868-6872.
- Keyzer, M.A., Merbis, M.D., Pavel, I.F.P.W., van Wesenbeeck, C.F.A. (2005) Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? *Ecological Economics* 55, 187-202.
- Klein Goldewijk, K., Beusen, A., Van Drecht, G., De Vos, M. (2011) The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecology and Biogeography* 20, 73-86.
- Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K.L., Kram, T., Riahi, K., Winkler, H., van Vuuren, D.P. (2014) A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change* 122, 401-414.
- Lambin, E.F., Meyfroidt, P. (2011) Inaugural Article: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* 108, 3465-3472.
- Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N. (2010) Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? *Global Ecology and Biogeography* 19, 769-782.
- Lilburne, L., Tarantola, S. (2009) Sensitivity analysis of spatial models. *International Journal of Geographical Information Science* 23, 151-168.
- Lindeskog, M., Arneth, A., Bondeau, A., Waha, K., Seaquist, J., Olin, S., Smith, B. (2013) Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa. *Earth System Dynamics* 4, 385-407.
- Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L. (2008) Prioritizing Climate Change Adaptation Needs for Food Security in 2030. *Science* 319, 607-610.

- Lobell, D.B., Field, C.B. (2007) Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters* 2, 014002.
- Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., Kato, E., Shukla, P.R., Yamagata, Y., Kainuma, M. (2011) An emission pathway for stabilization at 6 Wm⁻² radiative forcing. *Climatic Change* 109, 59-76.
- Metzger, M., Rounsevell, M., Acostamichlik, L., Leemans, R., Schroter, D. (2006) The vulnerability of ecosystem services to land use change. *Agriculture, Ecosystems & Environment* 114, 69-85.
- Montgomery, D.R. (2007) Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences* 104, 13268-13272.
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J. (2010) The next generation of scenarios for climate change research and assessment. *Nature* 463, 747-756.
- Muetzfeldt, R., Massheder, J. (2003) The Simile Visual Modelling Environment. *European Journal of Agronomy* 18, 345-358.
- Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Yong Jung, T., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., (2000) Special Report on Emission Scenarios, in: Nakicenovic, N., Swart, R. (Eds.). *Intergovernmental Panel on Climate Change (IPCC)*, Geneva.
- OECD/IEA, (2012) *WORLD ENERGY OUTLOOK 2012*. International Energy Agency, Paris.
- O'Neill, J., (2016) Review on antimicrobial resistance.
- O'Neill, B.C., Krieglner, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W. (in press) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*.
- O'Neill, B.C., Krieglner, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P. (2013) A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change* 122, 387-400.
- Ontl, T.A., Schulte, L.A. (2012) Soil Carbon Storage. *Nature Education Knowledge* 3.
- Phalan, B., Onial, M., Balmford, A., Green, R.E. (2011) Reconciling Food Production and Biodiversity Conservation: Land Sharing and Land Sparing Compared. *Science* 333, 1289-1291.
- Pinstrup-Andersen, P. (2009) Food security: definition and measurement. *Food Security*, 1, 5-7.
- Prestele, R., Alexander, P., Rounsevell, M., Arneth, A., Calvin, K., Doelman, J., Eitelberg, D., Engström, K., Fujimori, S., Hasegawa, T., Havlik, P., Humpenöder, F., Jain, A.K., Krisztin, T., Kyle, P., Meiyappan, P., Popp, A., Sands, R.D., Schaldach, R., Schüngel, J., Stehfest, E., Tabeau, A., van Meijl, H., van Vliet, J., Verburg, P.H.

- (2016) Hotspots of uncertainty in land use and land cover change projections: a global scale model comparison. *Global Change Biology*.
- Prieler, S., Fischer, G., van Velthuisen, H. (2013) Land and the food-fuel competition: insights from modeling. *Wiley Interdisciplinary Reviews: Energy and Environment* 2, 199-217.
- Pugh, T.A.M., Arneth, A., Olin, S., Ahlström, A., Bayer, A.D., Klein Goldewijk, K., Lindeskog, M., Schurgers, G. (2015) Simulated carbon emissions from land-use change are substantially enhanced by accounting for agricultural management. *Environmental Research Letters* 10, 124008.
- Reich, P.F., Eswaran, H. (2002) Global resources. In: Lal, R. (Ed.), *Encyclopedia of Soil Science*, pp. 607-611. Marcel Dekker, New York.
- Reilly, M., Willenbockel, D. (2010) Managing uncertainty: a review of food system scenario analysis and modelling. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, 3049-3063.
- Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A. (2009) A safe operating space for humanity. *Nature* 461, 472-475.
- Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W. (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *PNAS* 111, 3268-3273.
- Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P., Chivian, E. (2001) Climate Change and Extreme Weather Events; Implications for Food Production, Plant Diseases, and Pests. *Global Change and Human Health* 2, 90-104.
- Rounsevell, M.D.A., Pedrolí, B., Erb, K.-H., Gramberger, M., Busck, A.G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., Lindner, M., Lotze-Campen, H., Metzger, M.J., Murray-Rust, D., Popp, A., Pérez-Soba, M., Reenberg, A., Vadineanu, A., Verburg, P.H., Wolfslehner, B. (2012) Challenges for land system science. *Land Use Policy* 29, 899-910.
- Sallaba, F., Lehsten, D., Seaquist, J., Sykes, M.T. (2015) A rapid NPP meta-model for current and future climate and CO₂ scenarios in Europe. *Ecological Modelling* 302, 29-41.
- Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., Tarantola, S. (2008) *Global sensitivity analysis: the primer*. Wiley Online Library, West Sussex.
- Satterthwaite, D., McGranahan, G., Tacoli, C. (2010) Urbanization and its implications for food and farming. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, 2809-2820.
- Schimel, D., Stephens, B.B., Fisher, J.B. (2015) Effect of increasing CO₂ on the terrestrial carbon cycle. *PNAS* 112, 436-441.

- Shevliakova, E., Pacala, S.W., Malyshev, S., Hurtt, G.C., Milly, P.C.D., Caspersen, J.P., Sentman, L.T., Fisk, J.P., Wirth, C., Crevoisier, C. (2009) Carbon cycling under 300 years of land use change: Importance of the secondary vegetation sink. *Global Biogeochemical Cycles* 23.
- Smil, V. (2002) Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins. *Enzyme and Microbial Technology* 30, 205-311.
- Smith, B., Perentice, I.C., Sykes, M.T. (2001) Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography* 10, 621-637.
- Smith, B., Wårlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., Zaehle, S. (2014) Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. *Biogeosciences* 11, 2027-2054.
- Smith, P. (2013) Delivering food security without increasing pressure on land. *Global Food Security* 2, 18-23.
- SSP-Database, (2015) SspDb_country_data_2013-06-12. <https://secure.iiasa.ac.at/web-apps/ene/SspDb/>, last access: 2015-12-02.
- Tilman, D., Clark, M. (2014) Global diets link environmental sustainability and human health. *Nature* 515, 518-522.
- Tubiello, F.N., Salvatore, M., Ferrara, A.F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R.D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M.J., Srivastava, N., Smith, P. (2015) The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012. *Global Change Biology* 21, 2655-2660.
- Turner, B.L., Lambin, E.F., Reenberg, A. (2007) Land Change Science Special Feature: The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences* 104, 20666-20671.
- UN (2015) United Nations, Department of Economic and Social Affairs, Population Division World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241.
- van Ruijven, B., Urban, F., Benders, R.M.J., Moll, H.C., van der Sluijs, J.P., de Vries, B., van Vuuren, D.P. (2008) Modeling Energy and Development: An Evaluation of Models and Concepts. *World Development* 36, 2801-2821.
- van Vuuren, D.P., de Vries, B., Beusen, A., Heuberger, P.S.C. (2008) Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios. *Global Environmental Change* 18, 635-654.
- van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H. (2014) A new scenario framework for Climate Change Research: scenario matrix architecture. *Climatic Change* 122, 373-386.
- WB, (2012) The World Bank DATA. <http://data.worldbank.org/>, last access: 2012-09-14.
- Verburg, P.H., Mertz, O., Erb, K.-H., Haberl, H., Wu, W. (2013) Land system change and food security: towards multi-scale land system solutions. *Current Opinion in Environmental Sustainability* 5, 494-502.

WHO (2004) WHO fact sheet: The Impact of Pesticides on Health.

Wichelns, D., Oster, J.D. (2006) Sustainable irrigation is necessary and achievable, but direct costs and environmental impacts can be substantial. *Agricultural Water Management* 86, 114-127.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F.N., Herold, M., Gerber, P., Carter, S., Reisinger, A., van Vuuren, D.P., Dickie, A., Neufeldt, H., Sander, B.O., Wassmann, R., Sommer, R., Amonette, J.E., Falcucci, A., Herrero, M., Opio, C., Roman-Cuesta, R.M., Stehfest, E., Westhoek, H., Ortiz-Monasterio, I., Sapkota, T., Rufino, M.C., Thornton, P.K., Verchot, L., West, P.C., Soussana, J.-F., Baedeker, T., Sadler, M., Vermeulen, S., Campbell, B.M. (2016) Reducing emissions from agriculture to meet the 2 °C target. *Global Change Biology*.