

Understanding Implications of Key Economic Factors for Land Dynamics and Food Systems in a Changing World

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Summary

Human beings are currently facing a new set of intersecting challenges in a changing world, in which increasing population and income are placing unprecedented demands on agricultural goods. Beyond conventional economic concerns, climate change is generating additional strains that threaten to hammer away at global agricultural supply in general. The dominant economic strategies currently used to fulfill demand are also facing challenges, as productivity growth in the agricultural sector is decreasing, and agricultural trade still faces severe market distortion. Acknowledging these contemporary challenges, this dissertation takes into consideration three key economic factors – governance performance, productivity growth, and trade liberalization – and assesses their impacts on land dynamics and food prices in a changing world. Building upon an agro-economic dynamic optimization model known as MAgPIE, this dissertation firstly seeks to enhance representation of the economic factors in the model in the following ways: 1) modeling governance performance by using lending interest rates as discount rates to reflect associated risk-accounting factors; 2) applying multiple productivity indicators to assess future potential of global productivity growth under different socioeconomic conditions; and 3) modeling agricultural trade on the basis of a bilateral trade structure, in order to consider trade policy instruments directly, which in reality are bilateral in nature.

The research findings reveal that governance performance has a significant impact on technological progress and land productivity growth, especially for developing regions, such as Latin America, Sub-Saharan Africa, South Asia, and Southeast Asia. This, in turn, exerts impacts on land dynamics, including cropland expansion and deforestation. Aside from environmental impacts, governance performance affects livelihoods, as it influences food prices and trade patterns. Moreover, the dissertation suggests that global productivity growth is likely to continue, despite differences in possible socioeconomic conditions. However, the magnitude of the growth rate under each set of conditions will vary, according to different productivity indices. Differences in socioeconomic conditions lead to a spread in productivity growth in the crop sector, which will have profound implications for cropland expansion and food prices. Last but not least, the dissertation argues that liberalizing agricultural trade can buffer negative impacts from climate change on agricultural supply, limit increasing food prices in a scenario of high-end climate impacts on crop yields, and reduce cropland expansion on the global scale, though it may induce cropland expansion in certain regions due to changes in trade patterns. Synthesizing the findings from the individuals studies of which it is comprised, the dissertation is intended to enhance understanding of the trade-offs and synergies of economic options for agricultural outputs to keep pace with increasing demand and, thereby, contribute to the core discussion among agricultural economists on food production and its economic and environmental impacts.

Zusammenfassung

In einer sich verändernden Welt, in der Bevölkerungswachstum und steigende Einkommen die landwirtschaftlichen Kapazitäten in bisher ungekanntem Maße fordern, stehen die Menschen vor neuen Herausforderungen. Neben den gängigen wirtschaftlichen Belangen stellt der Klimawandel eine zusätzliche Belastung dar, die das globale Angebot an landwirtschaftlichen Gütern zu beeinträchtigen droht. Die vorherrschenden wirtschaftspolitischen Strategien, die derzeit zur Deckung der Nachfrage eingesetzt werden, stehen ebenfalls vor Herausforderungen, da das Produktivitätswachstum im Agrarsektor abnimmt und der Agrarhandel immer noch starken Marktverzerrungen ausgesetzt ist. In Anbetracht dieser Herausforderungen der Gegenwart berücksichtigt diese Dissertation die drei wichtigsten wirtschaftlichen Faktoren – Regierungsführung, Produktivitätswachstum und Handelsliberalisierung -, und bewertet deren Auswirkungen auf die Landnutzungsdynamik und die Lebensmittelpreise in einer sich verändernden Welt.

Aufbauend auf dem agrarökonomischen, dynamischen Optimierungsmodell MAGPIE wird im Rahmen dieser Dissertation die Repräsentation der wirtschaftlichen Faktoren im Modell auf folgende Weise erweitert und verbessert: 1) Modellierung der Governance-Leistung durch Verwendung von Zinssätzen als Diskontierungszinssätze, um die damit verbundenen Risikofaktoren abzubilden; 2) Anwenden mehrerer Produktivitätsindikatoren zur Abschätzung des zukünftigen Potenzials des globalen Produktivitätswachstums unter verschiedenen sozioökonomischen Bedingungen; und 3) Modellierung des Agrarhandels auf der Grundlage einer bilateralen Handelsstruktur, um handelspolitische Instrumente direkt untersuchen zu können, die in Wirklichkeit bilateraler Natur sind.

Die hier vorgestellten Forschungsergebnisse zeigen, dass die Governance-Leistung einen bedeutenden Einfluss auf den technologischen Fortschritt und das Wachstum der Flächenproduktivität hat, insbesondere für in der Entwicklung begriffene Regionen wie Lateinamerika, Afrika südlich der Sahara, Südasien und Südostasien. Dies wirkt sich wiederum auf die Landnutzungsdynamik aus, einschließlich der Ausdehnung von Ackerflächen und der Entwaldung. Neben Umweltauswirkungen beeinflusst die Governance-Leistung auch Lebensmittelpreise und das Handelsverhalten, und damit die Existenzgrundlagen vieler Menschen. Darüber hinaus legt die Dissertation nahe, dass sich das globale Produktivitätswachstum trotz unterschiedlicher sozioökonomischer Bedingungen wahrscheinlich fortsetzen wird. Die Größenordnung der Wachstumsrate unter den jeweiligen Bedingungen variiert jedoch, je nach verwendeten Produktivitätsindizes. Unterschiede in den sozioökonomischen Gegebenheiten führen zu einer Zunahme des Produktivitätswachstums im Ackerbau, was tiefgreifende Auswirkungen auf die Anbaufläche und die Lebensmittelpreise hat. Nicht zuletzt zeigen die Ergebnisse der Dissertation, dass die Liberalisierung des Agrarhandels negative Auswirkungen des Klimawandels auf das

landwirtschaftliche Angebot abfedern kann, den Anstieg der Lebensmittelpreise im Zuge von erheblichen klimabedingten Ertragseinbußen begrenzen und die Ausdehnung der Anbauflächen im globalen Maßstab verringern kann. In bestimmten Regionen kann es aufgrund von veränderten Handelsmustern zu einer Ausdehnung der Anbauflächen kommen.

In Zusammenschau der Ergebnisse aus den Einzelstudien vertieft die vorliegende Dissertation das Verständnis für potenzielle Zielkonflikte und Synergien von wirtschaftspolitischen Optionen, die darauf abzielen, die Produktionskapazitäten im landwirtschaftlichen Sektor der steigenden Nachfrage entsprechend auszubauen. Damit tragen die Forschungsergebnisse zu einer zentralen Diskussion unter Agrarökonomen über die Nahrungsmittelproduktion und ihre wirtschaftlichen und ökologischen Auswirkungen bei.

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[M]an has throughout history been continuously challenged by the twin problems of (a) how to provide himself with adequate sustenance and (b) how to manage the production and disposal. [...] Failure to make balanced progress along both fronts has at times imposed serious constraints on society's growth and development. The current environmental crisis represents, in my view, one of those reoccurring times in history when technical and institutional change in the treatment of residuals has lagged relative to progress in the provision of sustenance, conceived in the broad sense of the material components of consumption.

Vernon W. Ruttan (1971,
p707)

1 INTRODUCTION

1.1 Overview

The share of the contribution of the agricultural sector to economic growth has been constantly diminishing in both developing and developed countries, accounting for 4% of global GDP in 2017 and 1% and 8% for developed and developing countries, respectively. However, drawing on the most recent evidence and applying a range of methods, studies now propose that agricultural growth is, compared to other sectors, the most effective in poverty reduction (Christiaensen and Martin, 2018). Agricultural development is even more essential in the broader context, as it has impacts not only on food security and poverty reduction but also on ecosystems (Barrett et al., 2010; Sayer and Cassman, 2013). Before the 1960s, increasing output in the agricultural sector mainly depended on land expansion (Hansen and Prescott, 2002; Ruttan, 2002), leading to a global increase of 1,500 million hectares of cropland and 2,600 million hectares of grassland coming under agricultural use in the past three centuries (Lambin et al., 2003). The situation changed in the second half of the twentieth century (Fig. 1-1), as agricultural production tripled to meet increasing demand for agricultural products, while maintaining limited increases of agricultural land area used (Alston, 2018).

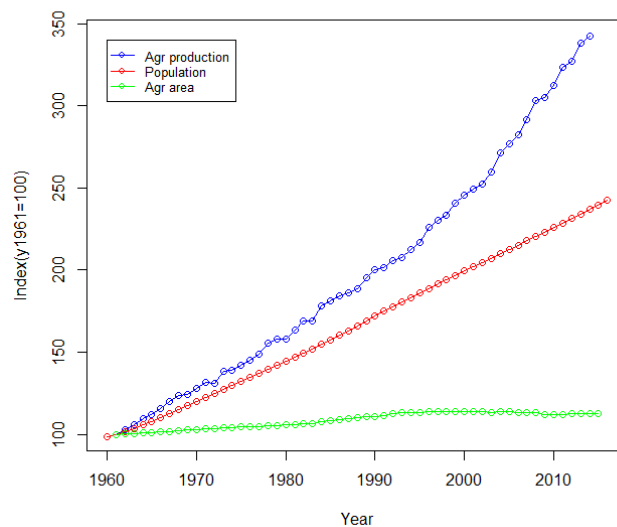


Fig. 1-1. Growth rates of global agricultural production, population, and agricultural area used, from 1960 to the 2000s.

Source: author's own calculations, based on data obtained from WDI 2018 and FAO 2018.

The fact that agricultural production has been increasing constantly to fulfill food demand rejects Malthus's hypothesis that exponential population growth would eventually outstrip arithmetic increase of food supply (Malthus, 2007). However, his prophecy might still come true, since humans are currently facing a new set of intersecting challenges in a changing world, in which increasing population and income are placing unprecedented demands on agricultural goods (Godfray et al., 2010; Foley et al., 2011). Key here is that income growth not only drives up food demand but also tends to alter dietary preferences. In the coming decades, increasing food demand is expected to mostly occur in poor countries, in which income growth is rising and income elasticity of demand for food also remains high (Ruttan, 2002). Even a combination of moderately high income and current rates of population growth could double food demand by 2050 (Ruttan, 2002). Increasing food demand, combined with limited natural resources (e.g., limited land availability), is likely to push food prices higher (Josling et al., 2010). Additionally, material demand, such as for bioenergy, further increases demand for agricultural output (Lotze-Campen et al., 2010), although a decoupling of food crops from bioenergy production might be partly achieved through second-generation bioenergy technology (Lotze-Campen et al., 2014). On the production side, increasing agricultural productivity due to technological improvement and liberalizing agricultural trade are key economic responses for keeping agricultural supply at the same pace as increasing demand (Ruttan, 2002; Anderson and Martin, 2005; Josling et al., 2010; Nelson et al., 2014; Alston, 2018). The former is directly related to increasing agricultural supply by enhancing resource-use efficiency and pushing upward the production frontier, while the latter

reallocates production among countries, based on comparative advantage, which acts to increase overall productivity. However, the economic strategies used to fulfill demand are also facing challenges, as productivity growth in the agricultural sector is decreasing (Alston, 2018) and agricultural trade faces more severe market distortion, compared to the industrial and service sectors (Anderson and Martin, 2005).

Beyond conventional economic concerns, climate change is inducing an additional challenge, as it hammers away at global agricultural supply in general (Brown and Funk, 2008; Lobell et al., 2011; Hertel, 2016). The observed rising global mean temperature (GMT) is exerting negative impacts on crop yields in general (Lobell et al., 2011), with some regions benefiting from climate change and others suffering (Parry et al., 1999; Müller et al., 2010). For the upper-end impacts of climate change, it is projected that the average biophysical yield of crops will decrease by 17% globally by 2050, compared with the reference scenario without climate impacts (Nelson et al., 2014). Vice versa, agricultural production have effects on ecosystems, often generating negative environmental externalities if feedback effects are not internalized by producers (Lopez, 1994). When further increasing agricultural outputs, the environmental impacts of agricultural production will remain a major concern. Increasing agricultural production also intensifies competition for natural resources, such as land, water, and energy (Godfray et al., 2010). One example is that agricultural land expansion leads to loss of forests and biodiversity (Chaplin-Kramer et al., 2015; Chaudhary and Kastner, 2016) and increases of land-use based CO₂ emissions (van Vuuren et al., 2017).

Jointly, these changing socioeconomic and biophysical conditions are adding enormous complexity into the search for solutions for feeding the world's growing population while seeking to preserve ecosystems. As pointed out by Ruttan in 1971, in his presidential address to the American and Applied Economics Association (AAEA), "failure to make balanced progress along both fronts has at times imposed serious constraints on society's growth and development".

Taking the above-outlined contemporary intersecting challenges into consideration, this dissertation aims to assess the impacts of governance performance, productivity growth, and agricultural trade liberalization on land dynamics and food systems. The research findings are expected to enrich our understanding of the trade-offs and synergies due to options for agricultural outputs to keep pace with increasing demand, when considering the economic and environmental impacts.

1.2 Theoretical perspectives and empirical evidence

1.2.1 Insights from institutional economics and theory of discounting

Beginning in the second half of the twentieth century, the role of institutions has become increasingly valued and discussed among economists. With the publication of Hardin's

“Tragedy of the Commons” (1968), discussion of institutions has been an important strand of the discussion oriented toward dealing with management of natural resources in local communities, especially with reference to the commons (Ostrom, 2005; Bromley, 2006; Hagedorn, 2008). Although the present dissertation addresses such issues on the global and regional levels, it benefits from institutional economics theories by interpreting institutions as humanly devised constraints regularizing human actions (North, 1990) and, thus, affecting human land-use behavior. I follow Bromley (2006) in analyzing institutions in the form of public policies, property rights, and norms, concentrating particularly on property rights over agricultural land.

Property rights – including state, private, common and open-access property rights – grant authority to dispose of and withhold benefit streams generated from resources (Bromley 2006). In the case of land use, for example, property rights create incentives, affecting agents’ calculations regarding costs and benefits of potential land-use patterns which, in turn, affect their land-use choices (Angelsen and Kaimowitz, 1999; Arnot et al., 2011). Security of property rights is central to the economics of development (Lin, 1992, 2012), as insecure property rights can induce high costs for technological investment (Angelsen 1999, Bohn and Deacon 2000, Culas 2007, Araujo et al. 2009), regardless of forms of tenure (Robinson et al., 2014). Developing countries observed to be undergoing large amounts of deforestation, for example, often exhibit weak governance performance, related to weak property rights and limited rule of law (Ferreira, 2004). More importantly, property rights are not retained by themselves but are, rather, contingent on the performance of governance (Bhattarai and Hammig 2001, Hagedorn 2008), as illustrated in an accumulating body of empirical observations from all over the world, on the country and local levels (Bromley, 1992; Bohn and Deacon, 2000; Ostrom, 2011; Wang et al., 2013; Yu and Farrell, 2013). Since the state is the ultimate enforcer of property rights (Bromley 2006), its performance, determined by the political and economic situation in a country, affects the effectiveness of public policies and property rights. Strong governance, meaning a stable political situation combined with good government accountability, is therefore expected to improve conditions for forest conservation (Deacon 1994, Bhattarai and Hammig 2001).

Although there is wide recognition of the importance of governance performance in land-use dynamics, it still remains technically difficult to simulate its impacts. Discount rates – the theories and methods of which are well summarized by Karp and Traeger (2013) – are a common instrument in quantitative modeling analysis involving forward-looking perspectives regarding resource uses and utilization maximization. The use of social discounting rates appeared early in Ramsey’s model (Ramsey, 1928; Benassy, 2011) and their conceptual reasoning was provided by Hotelling (1931), which later became a central feature of the overlapping generation model (Diamond, 1965). Application to environment issues was pioneered by Nordhaus (2007). From an intergenerational optimization point of view,

Weitzman argues that social discount rates should be at their lowest possible (Weitzman, 1998, 1994; Gollier and Weitzman, 2010). This strand has a strong focus on consumption and utility, as well welfare maximization, as it originates from addressing questions of economic growth. From an investment point of view, the effect of discount rates on resource depletion depends on substitution between capital and other inputs. High discount rates not only depreciate the future value of a resource stock but also reduce capital-investment incentives for resource extraction, both leading to depletion of the resource. In the case of deforestation, high discount rates provide disincentives for capital investment in agricultural production and encourage cropland expansion, which encroaches on forests, since lack of investment in crop yields needs to be compensated by additional cropland expansion (Deacon, 1994, 1999; Bohn and Deacon, 2000; Culas, 2007; Araujo et al., 2009). Adopting the discount-rates approach, the present study will use lending interest rates as discount rates to reflect risk-accounting factors associated with different governance scenarios.

1.2.2 Economics of productivity in the agricultural sector

Agricultural economists have been advocating the importance of technical change (TC)¹ for a long time, pointing out that very substantial increases in research & development (R&D) toward agricultural technologies will be required for food production to keep pace with growth in demand (Ruttan, 2002). TC is essential for increasing agricultural output by stimulating productivity and, thus, can contribute toward reducing poverty and infant mortality, while increasing per capita food supplies and life expectancy (Johnson, 2000). Technological progress associated with the green revolution of the 1960s successfully increased crop yields without requiring a corresponding expansion of cropland to meet the increasing food needs of Asia's growing population (Sayer and Cassman, 2013). In order to meet future agricultural demand in the context of population growth and changing dietary preferences, technological progress in the agricultural sector has become more important than ever (Wiebe et al., 2003; Tester and Langridge, 2010). The critical role of technology in promoting agricultural productivity and inclusive economic growth is widely recognized (Barrett et al., 2010), and the intrinsic properties of TC have been extensively studied (Arrow, 1962; Romer, 1986; Lucas, 1988; Romer, 1990). In contrast to the assumption of TC being exogenous in early neoclassical growth theory (Solow, 1957), it has been more recently found to be an endogenous process (Arrow, 1962; Romer, 1986; Lucas, 1988; Romer, 1990). In the agricultural sector, it can occur through the adoption of new crop varieties, improvements in management, and expansion of irrigation infrastructure (Griliches, 1957; Lin, 1991; Schneider

¹ Technical change and technological change are used interchangeably in the literature, although the former term refers to an improvement of existing techniques and the latter denotes a newly developed technique (Elster, 1983). The dissertation will mainly use the term of technological change through the texts but refer to technical change in the context of productivity and efficiencies analysis, the strand of which has a convention to use the term of technical change.

et al., 2011; Baker et al., 2012). Advancing agricultural technology is generally triggered by investment in R&D (Griliches, 1963) and can be associated with population pressure (Boserup, 1975). Factor-saving technologies (e.g., labor- or land-saving technologies) are spurred by changes in relative resource endowments and factor prices (Ruttan, 2002). For instance, technical change occurring during the green revolution was strongly geared toward land-saving by enhancing yields based on biological technologies (Murgai, 2001; Murgai et al., 2001).

It has been more than half a century since the concept of productivity residuals was introduced to agricultural economics by Schultz (1956), and agricultural economists are still striving to improve the measurement of productivity growth (Alston, 2018). Different methods have been employed to measure productivity, and such differences in methodology reflect conceptual differences between partial factor productivity (PFP) and total factor productivity (TFP). Only a few studies have been conducted to understand the future potential of productivity growth. The prediction of TFP in the current literature, for example, relies on simplified assumptions and limited time-series data, without considering possible future structural changes, such as changes in food demand, demography or biofuel demand.

Based on the above and relying on a partial equilibrium framework, focusing on land scarcity, and placing a strong emphasis on land-use dynamics, the present dissertation considers TC to be endogenous and will mainly take into consideration land-saving technologies. Furthermore, the present study aims to provide a holistic view of productivity growth by distinguishing between TFP and PFP and assess the potential of future productivity growth under different socioeconomic conditions.

1.2.3 Trade economics, agricultural trade, and environmental externalities

Agricultural trade plays an important role in distributing agricultural goods, which also improves efficiencies by stimulating productivity on the basis of comparative advantages. International trade has been a core of economics, and agricultural trade has been intensively studied ever since the establishment of the WTO in 1995 (Karp and Perloff, 2002). From the 1950s through the early 2000s, global trade volume increased 17 fold, more than three times faster than the growth of global GDP (Anderson and Martin, 2005). Agricultural trade has been expanding at a faster pace than the growth of agricultural production, although the share of agricultural trade compared to total trade has been declining, and its trade growth rate is the lowest among all the sectors (Bruinsma, 2003; Anderson and Martin, 2005). Compared to the manufacturing sector, intra-firm trade is seldom undertaken in the agricultural sector, due to high trade protection levels and the intrinsic characteristics of agricultural production, which relies on agro-biophysical conditions (Bruinsma, 2003).

The potential gains from agricultural liberalization are estimated to be large, with developing countries gaining much more from further global trade reform (Anderson and Martin, 2005).

Consequently, trade policy has become one of the most important issues in agricultural economics (Sumner and Tangermann, 2002). Stringent agriculture trade policy, such as restricting exports, has been found to do more harm than good (Headey, 2011). The drastic rise in international rice prices in 2008, for example, has been partly attributed to the trade policies deployed by the main exporters of rice (e.g., Thailand, India and Vietnam). Although international trade theory is essential for understanding agricultural trade-related policy issues (Karp and Perloff, 2002), the study of the economics of international trade in agricultural and food products is still a relatively new area of specialization in the field of agricultural economics (Josling et al., 2010). The neoclassical economics perspective offers a powerful lens for understanding trade issues, and the theory of comparative advantage lies at the heart of the economics of agricultural trade. Together with the first theorem of welfare economics, it provides the intellectual basis for supporting trade liberalization (Karp and Perloff, 2002). Also taken from neoclassical economics, partial equilibrium and computable general equilibrium (CGE) models are widely used to estimate the trade and welfare effects of existing policies and the potential of policy reform measures (Karp and Perloff, 2002).

In spite of the benefits of agricultural trade, generated largely through comparative advantage, the negative impacts of such trade have been attracting scientific attention. Environmental externalities inherent in agricultural production from the use of land have been found to be reinforced by international trade (Henders and Ostwald, 2014). In line with this argument, and building on theoretical models, Lopez (1994) and Karp (2008) conclude that agricultural trade inevitably leads to deforestation, when feedback on production from the environment is not internalized by agricultural producers. These studies were undertaken to respond to and update the debate on the up and down sides of agricultural trade, which can be dated back to the consensus drawn by Anderson (1992) and Lutz (1992), proposing that positive gains from trade outweigh losses, although negative environmental effects in developing countries might occur. In the past decade, climate change issues have substantially increased as the focus of agricultural trade analysis (Josling et al., 2010), with agricultural trade being increasingly perceived among agricultural economists as a key adaptation option in the face of climate change (Reilly and Hohmann, 1993; Fischer et al., 1994; Nelson et al., 2014). As a form of economic adjustment, agricultural trade could help to alleviate the challenges posed by climate change by benefiting from comparative productivity advantages between countries (Ruiter et al., 2016). Liberalizing trade is expected to reduce market distortion and, therefore, increase total agricultural welfare, while also slowing the increase of food prices (Stevanović et al., 2016) and, in the meantime, reducing cropland expansion caused by agricultural production on the global level (Schmitz et al., 2012). To unleash the benefits of trade, agriculture-related trade barriers need to be reduced to increase market access. As trade policy is bilateral in nature (Tongeren and Meijl, 1999), the present study aims to incorporate a bilateral trade structure with associated trade costs (e.g.,

trade tariffs and trade margins) that directly affect cost competitiveness to analyze potential trade-offs between food security and cropland expansion due to trade liberalization in the context of high-end climate impacts on crop yields.

1.3 Research approach

1.3.1 Modeling framework

Economic sector models often tend to simplify the biophysical dimensions of a given problem. This can be considered a sensible approach, when research questions related to the industrial or service sectors do not involve many biophysical factors. However, for studies related to the agricultural sector, incorporating detailed biophysical information becomes crucial, because agricultural production essentially depends on natural resources that are spatially heterogeneous. On the other hand, biophysical models, often operating on fine geographic grids, are likely to simplify economic mechanisms which are essential for understanding anthropogenic impacts on ecosystems. In terms of economic dimensions, production, demand, market mechanisms, and technological development affect agricultural activities and exert impacts on ecosystems. Consequently, models neglecting economic mechanisms, such as the price responsiveness of demand and supply, often fail to accurately estimate changes in production, cropland use and crop prices (Baldos and Hertel, 2013). Human activities have profound impacts on land systems, but they also respond to system changes via feedback loops (Rounsevell and Arneth, 2011). To advance our understanding of socio-ecological systems and issues related to sustainable development, it is necessary to take into account both components by modeling economic behaviors and biophysical processes at the same time (Lotze-Campen et al., 2010; Baldos and Hertel, 2013; Verburg et al., 2016). The Model of Agricultural Production and its Impact on the Environment (MAgPIE) strives to achieve such a balanced view on the economic and biophysical dimensions of a problem and is, therefore, the tool of choice in the following analyses.

MAgPIE is a partial equilibrium, agro-economic model for the optimization of land use and production patterns, under given agricultural demand and subject to spatially explicit biophysical constraints (Lotze-Campen et al., 2008; Popp et al., 2014). The objective function of the model is fulfilling food, livestock and material demand at minimum global production costs, under certain socioeconomic and biophysical constraints (Lotze-Campen et al., 2008). The model covers the most dominant food, feedstock, and livestock production types for ten world geographic regions (Fig. 1-2), the classification of which is based on the geo-economic conditions of each country. For reducing computational requirements to a feasible level, while preserving key information and increasing accuracy, clustering methods are used to aggregate spatial grid cells in the same regions to the cluster level, to obtain simulation units, on which the cost minimization problem is solved (Dietrich et al., 2013). The recursive optimization feature of the model implies that it solves for an optimum for each time step.

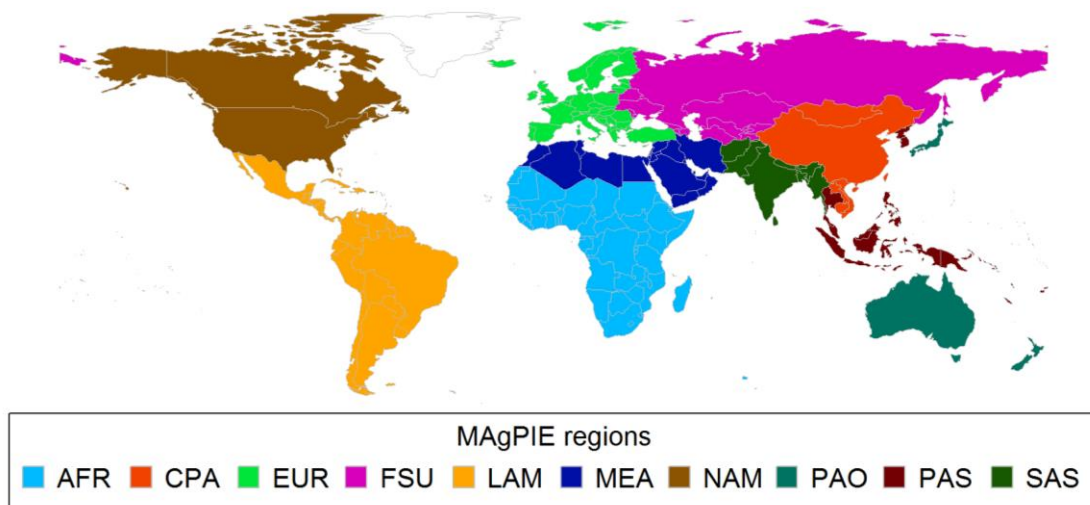


Fig. 1-2. MAgPIE regions. AFR is Sub-Saharan Africa; CPA includes China and other centrally planned countries in East and Southeast Asia; EUR is Europe; FSU contains regions from the former Soviet Union; LAM is Latin America; MEA is the Middle East and North Africa region; NAM refers to the United States and Canada; PAO is the Pacific OECD, excluding South Korea (i.e., Japan, Australia, New Zealand); PAS is mainly island countries in Southeast Asia; SAS includes India, Pakistan and other countries in South Asia.

When applying MAgPIE, the amount of food demand for crop and livestock products in the future is based on exogenous projections of future population and income growth as well as likely changes of dietary preference, determined by the projected number of consumers and their per-capita consumption (Bodirsky et al., 2015). Material demand is assumed to grow proportionally to food demand. Regional feed demand is driven by livestock products, transferred to the quantity of livestock supply. Specific livestock-system feed baskets are prescribed in accordance with the intensification degree of livestock systems in each world geographic region (Weindl et al., 2017). Within MAgPIE, biophysical constraints, such as crop yield potential and water availability, are derived from the Lund-Potsdam-Jena managed Land (LPJmL) global crop, hydrology and vegetation model (Müller and Robertson, 2014; Müller et al., 2017), and land availability is set at the 0.5 degree grid level (Krause et al., 2013). The LPJmL model is used to derive consistent sub-national yield patterns for current crop varieties, carbon stocks, water withdrawals and water availability.

Agricultural trade, increase of agricultural yields through augmenting R&D investment, and land expansion are the primary means of fulfilling food and material demand. Increasing agricultural yield through technological investment is implemented as a surrogate for crop productivity, that is, land-use intensity (Dietrich et al., 2014). MAgPIE assumes a decreasing marginal effect of technological investment on land-use intensity, without, however, imposing upper limits on land-use intensity levels. Factor requirement costs per area for production inputs rise along with growth of land-use intensity. International trade is

implemented in the model based on self-sufficiency ratios and regional comparative advantages to reallocate production among regions (Lotze-Campen et al., 2008; Schmitz et al., 2012). Socioeconomic constraints, such as trade liberalization in terms of reduction of self-sufficiency rates, are prescribed at the regional level to determine inter-regional reallocation of agricultural production, while intra-regional trade is not taken into account. The major associated costs are technological investment, land conversion costs, production costs for input factors, domestic transportation costs, and costs for expanding irrigation infrastructure.

1.3.2 Model extension and development

MAGPIE has been used in studies focusing on a spectrum of topics, including climate-change adaptation and long-run food security issues, and can provide a basis for analyzing problems related to sustainability issues (Lotze-Campen et al., 2008; Schmitz et al., 2012; Dietrich et al., 2014; Popp et al., 2014). In order to address the research questions considered in the dissertation, I introduce and develop new features for MAGPIE. The first way in which I extend it is to use regional lending interest as a risk-accounting factor associated with investment decisions to capture heterogeneous governance performance across regions. Country-level lending interest rates from 1995 and 2005 are aggregated according to each country's GDP; then taking the average over the period for each region. Detailed information regarding this can be found in the methods section of **Chapter 2**. A further development is estimating the impacts of GDP per capita on risk-accounting factors using country-level panel data (**Chapter 4**), which is meant to facilitate development of governance scenarios by introducing the feature of temporal dynamics, dependent on different assumptions regarding socioeconomic conditions in specific regions.

The second extension of the model is focused on estimating a multi-factor productivity index to assess future potential of global crop productivity growth, additional to information from land-use intensity measurement (**Chapter 3**). Regional TFP change is estimated for each world region as an output Malmquist productivity index (MPI), which is based on estimates of the Shephard output distance function using the data envelopment analysis (DEA) method to construct a piece-wise linear production frontier for each year in the sample (Färe et al., 1994; Nin et al., 2003; Coelli and Rao, 2005). The MPI can be decomposed to distinguish shift of production frontier and catch-up to the frontier. Moreover, I seek to provide consistent estimation of global MPI by adapting the method developed by Färe and Zelenyuk (2003) and Zelenyuk (2006) to construct a weighted average index that is based on the distance functions estimated from regional data with appropriate weighting.

The third way in which I extend the MAGPIE model has to do with implementing agricultural trade fully based on cost competitiveness (**Chapter 4**). Studies analyzing agricultural trade liberalization often focus on market access, export subsidies, and domestic support, as these are the three identified pillars for continuous trade reform of the WTO's Doha Development

Round negotiations (Anderson and Martin, 2005). Since the Uruguay Round Agreement of the 1980s and 1990s, improving market access has been one of the core discussion topics among researchers and policy makers. Reducing border protection tariffs was further discussed in the consecutive Doha Round negotiations, although a conclusion had not been reached. A model operating directly on the underlying driving factors of trade patterns, such as trade tariffs and trade margins that affect cost competitiveness, would be preferable to one only based on self-sufficiency rates. Hence, based on neoclassical trade theories, by assuming homogenous goods, a structure of bilateral trade flows and associated trade costs (i.e., trade margins and trade tariffs) is adapted into the overall MAgPIE modeling framework. Calibration of net trade flows is achieved by calibrating net trade volumes to 1995 levels through imposing additional costs which penalize deviation from previous trade positions. This is in line with the tariff-rate quota (TRQ), which is an additional tariff to the existing specific duty tariffs already built into the model.

1.4 Structure of the dissertation

The present study aims to encompass three key economic factors – governance performance, productivity growth, and trade liberalization – in the contemporary context of growing incomes and populations facing climate change, seeking to understand their environmental and socioeconomic impacts, particular with regard to land dynamics and food scarcity. Each of the factors is closely analyzed in one of the following three chapters.

In **Chapter 2**, the study incorporates governance factors into MAgPIE to simulate governance impacts on land-use patterns at the global scale and evaluate their implications for development issues, including agricultural yield growth, food prices and changes in agricultural trade patterns. Due to the difficulties of including governance indicators directly into numerical models, lending interest rates are used as discount rates to reflect risk-accounting factors associated with different governance scenarios. In addition to a reference scenario, three scenarios with high, low and divergent discount rates are formed to represent weak, strong and fragmented governance.

Chapter 3 aims at improving our understanding of the future potential of productivity growth by analyzing long-term productivity changes in the crop sector at the global and regional levels. Here I use a two-step approach, firstly simulating endogenous land-use intensity growth under future socioeconomic scenarios by employing MAgPIE and then estimating TFP changes by applying a non-parametric estimation method. This approach enables projection of PFP changes induced by endogenous technical change and cropland expansion and provides a basis for estimating TFP change by taking into account possible structural change.

Chapter 4 focuses on the impacts of trade policy by analyzing the impacts of agricultural trade liberalization on cropland dynamics and food prices in the context of high-end climate impacts on crop yields. A structure of bilateral trade flows and associated trade tariffs and margins

are adapted into MAGPIE to facilitate the analysis, and net trade patterns are calibrated according to historical data in the year 1995. Moreover, additional scenarios of governance performance are included to consider institutional barriers to climate adaptation concerning risks associated with investment in agricultural technologies.

Chapter 5 synthesizes the main findings presented in the individual analyses of the previous chapters. Methodological contributions, policy implications, as well as caveats and scope for future research are discussed.

Each of the chapters is self-contained and represents an individual analysis addressing a specific research question. The chapters are, however, strongly interconnected in terms of both theory and method and have been developed simultaneously to a large extent.

1.5 Statement of author contributions

This dissertation is written as a monograph, consisting of a published peer-reviewed paper and two conference papers. The research for this dissertation was conducted under the auspices of the Land-use Group at the Potsdam Institute for Climate Impact Research. I confirm myself to be the lead author for all of the work assembled here. Details regarding my co-authors and their individual contributions are clarified below.

Chapter 2 is adapted based on the following published article: Wang, X., Biewald, A., Dietrich, J. P., Schmitz, C., Lotze-Campen, H., Humpenöder, F., Bodirsky, B. L. & Popp, A. 2016. Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics*, 122, 12-24. doi: 10.1016/j.ecolecon.2015.11.018.

Together with Hermann Lotze-Campen and Jan Philipp Dietrich, I developed the research idea and methodological approach of the paper. Anne Biewald, Jan Philipp Dietrich, Hermann Lotze-Campen, and I designed scenarios for the analysis. I collected and processed the data and implemented the model features, operated the simulations, and wrote the manuscript. Hermann Lotze-Campen, Jan Philipp Dietrich, Anne Biewald, Christoph Schmitz, Florian Humpenöder, Alexander Popp, and Benjamin Leon Bodirsky contributed to the development of the overall modeling framework and provided comments on the manuscript.

Chapter 3 is adapted based on a conference paper presented at the International Conference of Agricultural Economists (ICAE) in 2015: Wang, X., Dietrich, J. P., Popp, A., Biewald, A., Lotze-Campen, H., Bodirsky, B. L., Humpenöder, F. Potential Land-Use Futures: Applying Different Indicators for Assessing the Endogenous Trade-offs Between Cropland Expansion and Intensification. ICAE 2015, Milan.

Jan Philipp Dietrich, Hermann Lotze-Campen, and I developed the research idea. Jan Philipp Dietrich and I developed and implemented the research method, and I conducted the analysis and wrote the manuscript. Jan Philipp Dietrich, Alexander Popp, Anne Biewald, Hermann Lotze-Campen, Benjamin Bodirsky, Florian Humpenöder provided comments. In a later

version, Bernard Bruemmer and I contributed to the method of improving estimation of global productivity changes, and I implemented the method.

Chapter 4 is adapted based on a conference paper presented at the International Conference of Agricultural Economists (ICAE) in 2018: Wang, X., Dietrich, J. P., Lotze-Campen, H., Biewald, A., Munson, T. S., Mueller, C. Trading More Food in the Context of High-End Climate Change: Implications for Land Displacement through Agricultural Trade. ICAE 2018, Vancouver.

Jan Philipp Dietrich, Hermann Lotze-Campen, and I developed the research idea. Together with Jan Philipp Dietrich, Hermann Lotze-Campen, and Anne Biewald, I developed the research method. Anne Biewald and I collected the GTAP data, and I processed all the data and parameterized all the variables. I carried out model implementation and analysis and wrote the manuscript. Christoph Mueller provided LPJmL outputs for the analysis. Todd S. Munson, Anne Biewald, Jan Philipp Dietrich, and I contributed to the development of an early version of calibration methods based on solving a bi-level optimization programming problem in MAgPIE.

2 TAKING ACCOUNT OF GOVERNANCE: IMPLICATIONS FOR LAND-USE DYNAMICS, FOOD PRICES, AND TRADE PATTERNS

Abstract

Deforestation mainly caused by unsustainable agricultural expansion, results in a loss of biodiversity and an increase in greenhouse gas emissions, as well as impinges on local livelihoods. Countries' governance performance, particularly with respect to property rights security, exerts significant impacts on land-use patterns by affecting agricultural-yield-related technological investment and cropland expansion. This study aims to incorporate governance factors into a recursive agro-economic dynamic model to simulate governance impacts on land-use patterns at the global scale. Due to the difficulties of including governance indicators directly into numerical models, I use lending interest rates as discount rates to reflect risk-accounting factors associated with different governance scenarios. In addition to a reference scenario, three scenarios with high, low and divergent discount rates are formed to represent weak, strong and fragmented governance. The study finds that weak governance leads to slower yield growth, increased cropland expansion and associated deforestation, mainly in Latin America, Sub-Saharan Africa, South Asia and Southeast Asia. This is associated with increasing food prices, particularly in Sub-Saharan Africa and Southeast Asia. By contrast, strong governance performance provides a stable political and economic situation which may bring down deforestation rates, stimulate investment in agricultural technologies, and induce fairly strong decreases in food prices.

Keywords: governance, deforestation, cropland expansion, food prices, and land-use intensity

2.1 Introduction

Forests contain large carbon stocks, storing 20 to 100 times more carbon per unit area than agricultural land (Upadhyay et al., 2005). It is estimated that 247 Gt carbon were stored in over 2.5 billion hectares of forest in the early 2000s in Asia, Latin America and Sub-Saharan Africa (Saatchi et al., 2011). In addition, tropical forests preserve a high level of biodiversity, retaining 75% of the primary vegetation (Myers et al., 2000), which helps enhance the resilience of such ecosystems to external shocks (Fischer et al., 2006). However, in the last two decades, about 290 million hectares of forest have been lost due to anthropogenic land conversion (FAO, 2012). The expansion of agricultural land, including cropland and grassland, is the major driver of deforestation (Eliasch, 2008). Between 1980 and 2000 more than 83% of new cropland was established on former forest area, especially in Latin America, Sub-Saharan Africa and Southeast Asia (Gibbs et al., 2010). The greatest expansion of grassland, by about 42 million hectares, occurred in Latin America (Gibbs et al., 2010). In a global study of tropical forests, conversion to agricultural land accounted for around 56% of total forest change (Barbier et al., 2005). Around 60% of deforestation in Africa was due to the conversion of forests to small-scale agriculture, whereas conversion to large-scale agriculture occurred mainly in Latin America and Asia (Barbier et al., 2005). Deforestation and forest degradation contributed to 12–20% of global anthropogenic carbon emissions in the last two decades (van der Werf et al., 2009).

Various drivers of agricultural land expansion such as increasing food demand due to population growth, trade liberalization, and other direct forces of deforestation such as commercial logging and firewood consumption have been studied in the literature (Capistrano, 1994; Cropper and Griffiths, 1994; DeFries et al., 2010; Hosonuma et al., 2012; Schmitz et al., 2012; Sharma, 1992). It has been suggested that underlying factors need to be distinguished from direct and intermediate causes to better understand the process of deforestation (Angelsen and Kaimowitz, 1999), and among such underlying factors, institutions and macroeconomic factors are fundamental to forest conservation (Galinato and Galinato, 2013; Geist and Lambin, 2002).

Institutions are humanly devised constraints that regularize human actions (North, 1990), and thus they affect human land-use behavior. Bromley (2006) emphasizes that institutions are represented in the form of public policies, property rights and norms. Property rights are the control of benefit streams generated from resources (Bromley, 2006). They include state property rights, private property rights, common property rights and open access (Bromley, 2006). In the case of land use, property rights often refer to land tenure or ownership. They create incentives which affect the agents' calculation of costs and benefits of their land-use patterns, which in turn affect their choice of land-use activities (Angelsen and Kaimowitz, 1999). Insecure property rights can therefore signal high costs for technological investment

due to high risks, and lead to unregulated and undesired deforestation with the purpose of creating new agricultural land (Angelsen, 1999; Araujo et al., 2009; Bohn and Deacon, 2000; Culas, 2007; Yu and Farrell, 2013). Due to the risks and uncertainties resulting from insecure land ownership, the discount rates for calculating present value of land use in the future are higher than they would be under secure property rights (Araujo et al., 2009). The effect of discount rates on resource depletion depends on the substitution between capital and other inputs. High discount rates not only depreciate the future value of a resource stock leading to the depletion of the resource, but reduce the capital investment incentives for resource extraction which would defer depletion. In the case of deforestation, high discount rates provide disincentives for capital investment in agricultural production and encourage cropland expansion which encroaches forests, since a lack of investment in crop yields has to be compensated by additional cropland expansion (Araujo et al., 2009; Bohn and Deacon, 2000; Culas, 2007; Deacon, 1994, 1999).

Property rights are not retained by themselves, but they are rather contingent on the performance of governance (Bhattarai and Hammig, 2001; Hagedorn, 2008; Wang et al., 2013; Yu and Farrell, 2013). Without well enforced land rights, forests fall into an open access situation which leads to forest degradation caused by a free-riding problem. Since the state is the ultimate enforcer for private and common property rights (Bromley, 2006), its performance, determined by the political and economic situation in a country, affects the effectiveness of public policies and property rights. We can therefore expect that a country with strong governance, i.e., a stable political situation combined with good government accountability, will improve forest conservation (Deacon, 1994; Bhattarai and Hammig, 2001).

Global land-use models have been used in several studies to assess the driving forces for deforestation such as demographic change, trade liberalization and economic growth (Verburg et al., 2008; Popp et al., 2010; Schmitz et al., 2012; Valin et al., 2013; Popp et al., 2014). Using global models instead of micro-level econometric models enables the analysis of such global underlying factors that determine regional land-use patterns. However, institutional factors are widely missing in global analyses so far, and their impacts have not been examined on a global basis, although the importance of policy and institutions has been extensively discussed in the theoretical literature and studied at a local level (Geist and Lambin, 2002). In this study, governance factors are incorporated into MAGPIE (Lotze-Campen et al., 2008; Popp et al., 2010, 2014), to analyze the impacts of governance on land use and its implication for development issues, such as agricultural yield growth, food prices and changes in trade. The following specific questions will be examined: (1) how does governance performance affect deforestation, GHG emissions, cropland expansion, and productivity in the crop sector? (2) how are food prices affected by governance performance, particularly in developing countries?, and (3) what are the effects of governance on agricultural trade?

The remainder of the chapter is organized as follows. Section 2.2 introduces the model employed for simulating impacts of governance on land use. Section 2.3 presents data on governance performance and discount rates, and a description of governance scenarios. Results about impacts of governance on the biophysical and social dimensions are presented in Section 2.4. Section 2.5 discusses the findings, and Section 2.6 draws conclusions.

2.2 Simulation methods

The MAgPIE model is employed to simulate governance impacts on land-use dynamics. Based on the review of theoretical and empirical analyses in the introduction, this study focuses on deforestation induced by creating new cropland, and includes macroeconomic and governance factors, as they are assumed to exert an impact on yield-related agricultural technological investment as well as cropland expansion. Assuming the world is experiencing moderate trade liberalization, in order to satisfy the growing regional food demand at minimum production costs, the model can either invest in R&D (Dietrich et al., 2014) for yield-increasing TC or in cropland expansion. The presented simulation covers the period from 1995 to 2050 at 5-year intervals with 700 clusters (simulation units) based on a k-means clustering algorithm of aggregating 59199 spatial grid cells (Dietrich et al., 2013). The optimization process is computed at the cluster level.

The annuity approach is adopted to distribute the costs of yield-related technological investment and cropland conversion costs occurring in the current time step into the future. A time horizon of 30 years has been adopted, since this is commonly practiced in agricultural investment. This study uses an annuity factor, where payments are made at the beginning of each period, since costs already occur in the first period in the model.

$$annuity_i = \frac{1 - (1 + r_i)^{-t}}{\frac{r_i}{1 + r_i}}, \quad (2.1)$$

where r_i is a discount rate for an economic world region i . Through the annuity, the value of the discount rates which depend on governance performance, affect land use choices in terms of costs related to R&D investment to increase yields and costs of conversion from forests to cropland. Using this method, the costs occurring in the current time step are equally distributed over six 5-year simulation periods (a planning horizon of 30 years), in which the costs of the first period are considered as sunk costs. The same holds true for other investments in the model such as costs associated with expansion of irrigation infrastructure and emission abatement payments. Let t denote a simulation time step, j a spatial cluster, v a crop product belonging to a set of crop products V , and w a water supply type including rain-fed and irrigation sources. C_t^1 are R&D investment costs for the time step t in the optimization process, given as

$$C_t^1 = p^{tcc} \sum_i \{x_{i,t}^{tc} [\frac{1}{|V|} \sum_v p_{i,v,t,i}^{\tau_1} f_{t,i}^{growth}(x_{i,t}^{tc}, x_{i,t-1}^{tc}, \dots, x_{i,1}^{tc})]^{p^{exp}} \sum_{j,v,w} x_{t-1,j,v,w}^{area} / annuity_i\},$$

$$f_{i,t}^{growth}(x_{i,t}^{tc}, x_{i,t-1}^{tc}, \dots, x_{i,1}^{tc}) = \prod_{\theta=1}^t (1 + x_{i,\theta}^{tc}), \quad (2.2)$$

where p^{tcc} are technological change costs accounting for discount rates, expected lifetimes and general costs [US\$/ton]; $p_{i,v}^{\tau 1}$ are agricultural yields in the first simulation time step for each crop in each region; p^{exp} is a correlation exponent between land-use intensity and technological change costs; $f_{i,t}^{growth}(x_{i,t}^{tc}, x_{i,t-1}^{tc}, \dots, x_{i,1}^{tc})$ is the growth function describing the aggregated yield increase due to productivity growth, induced by technological investment, compared to the level in the starting year for each time step t and region i ; $x_{t,j,v,w}^{area}$ and $x_{t-1,j,v,w}^{area}$ are cropland area in the time step t and $t - 1$. The TC is simulated based on a measure for agricultural land-use intensity for all the crops, $x_{i,\theta}^{tc}$ for $\theta = 1, \dots, t$, taking into consideration only human-induced productivity changes (Dietrich et al., 2012, 2014). For simplification, the study assumes the same effect measure for productivity (Turner and Doolittle, 1978; Lambin et al., 2000; Shriar, 2000). In this study, I refer to land-use intensity as the former one, equivalent to a type of PFP, due to a potential suite of changes in management and increase in technological improvements. With the implementation of TC in the model framework, crop yield can increase beyond the potential yields simulated by the vegetation model LPJmL, because the model takes only current production conditions into account, e.g., current genetic varieties. Through technological progress, development of new crop varieties or new management approaches are promoted that cannot only close the current yield gaps, but also lift the future yields beyond current yet unknown biophysical yield limits. However, the model takes into account the difficulty of pushing the yield frontier ever further. As shown above, TC investment is an exponential function of land-use intensity growth, which implies that achieving one additional unit increase of yield increase in a subsequent time step is more expensive than in the previous steps. As an alternative to technological progress, expanding cropland into other types of land, e.g., forest or grassland, can also provide a necessary increase in crop production. C_t^2 are the costs of creating new cropland through land conversion for each time step t in the optimization process which is simulated as

$$C_t^2 = \sum_i \{p_i^{lcc} \sum_{j,v,w} (x_{t,j,v,w}^{area} - x_{t-1,j,v,w}^{area}) / annuity_i\}, \quad (2.3)$$

where p_i^{lcc} is related land conversion costs for each region (US\$/ha). Yields for newly converted cropland are not the same as for existing cropland, but are determined by LPJmL based on soil and climate conditions.

2.3 Data and Scenarios

I firstly check the relationship between discount rates used in this analysis and governance indicators, both of which are derived from the World Development Indicators (The World Bank, 2018). The aggregate governance indicator estimates governance performance across 215 economies over the period 1996–2011, with a relatively large coverage of the world.

Strong governance refers to good government accountability, political stability, high government effectiveness, high regulatory quality, rule of law and little corruption. Economy-wide governance indicators have been shown to be good measures for governance in the agricultural and forest sectors, since a firm-level business environment survey conducted by the World Bank indicates that mean responses about governance in these two sectors are not significantly different from those across all sectors (Ferreira and Vincent, 2010). However, due to the difficulties of including governance indicators directly into the model, which is a common problem when studying governance impacts with numerical models (McNeill et al., 2014), lending rates considered as discount rates are used as proxy for governance indicators. According to the definition of lending interest rates by the World Bank, it refers to the bank rate that usually meets the short- and medium-term financing needs of the private sector. The lending rates, to some extent, reflect investment risks which are often related to unstable economic and political situation in different countries. For instance, a short-run discount rate ranges from 10% to 12% in developing countries, and from 4% to 6% in developed countries. From an investment point of view, the rate could be even higher, up to 25% (IPCC, 2007). To make sure that using lending rates as discount rates can represent governance performance, a correlation analysis is conducted to check the relationship between governance performance and discount rates. Results of the correlation analysis indicate that lending interest rates are positively correlated with deposit interest rates (correlation coefficient = 0.87) and real interest rates (correlation coefficient = 0.59), but negatively correlated with governance indicator (correlation coefficient = -0.55) and log transformation of GDP per capita (correlation coefficient = -0.62) (Fig. A-2 in Appendix A). All the correlation coefficients are significant at 99.99% level based on the sample. GDP is used as a weight to aggregate country-level discount rates data to MAgPIE region-level data. Because the model simulates land use starting from 1995, I aggregate the country-level lending interest rates from 1995 and 2005 according to each country's GDP, and then take the average for each region, as shown in Tab. 2-1. For FSU and LAM, because of exceptionally unstable political and economic situation in the 1990s, I use the data from 2000 and 2010.

Tab. 2-1. Discount rates used for representing different governance scenarios.

World regions	Strong governance	Reference	Weak governance	Fragmented governance
	Low discount rates	Lending rates	High discount rates	Mixed discount rates
AFR	0.11	0.22	0.33	0.33
CPA	0.04	0.09	0.13	0.13
EUR	0.04	0.09	0.12	0.04
FSU	0.08	0.16*	0.24	0.24
LAM	0.12	0.25*	0.37	0.37
MEA	0.06	0.12	0.18	0.18
NAM	0.03	0.07	0.1	0.03
PAO	0.02	0.04	0.06	0.02
PAS	0.05	0.11	0.16	0.16
SAS	0.07	0.13	0.20	0.20

Note: regional specified discount rates in FSU and LAM are weighted average lending rates between 2000 and 2010.

In the current version of MAgPIE, the discount rate for all world regions is set to 0.07, which is a common practice for evaluating non-monetary environmental values (Newell and Pizer, 2003). The theories and empirical analysis discussed previously make it clear that regionally specified discount rates, rather than an identical global discount rate, represent a better picture of the governance situation of a region, which is expected to exert impacts on cropland expansion and agricultural technological investment. Model validation is conducted by comparing simulated results of cropland expansion with historical data from FAO and two other models results. We find that the regionally specified discount rates allow for a better simulation of cropland expansion, compared with simulations using the global identical discount rate (Fig.A-3 in Appendix A). Four governance scenarios are covered in terms of governance performance convergence: reference scenario, weak governance scenario, strong governance scenario and fragmented governance scenario. Lending interest rates are used as discount rates in the reference scenario, while the reference discount rates are multiplied by factors of 0.5 and 1.5 respectively to represent hypothetical strong and weak governance scenarios (Tab. 2-1). Weak governance, referring to e.g., corruption, political instability, insecure property rights, lack of regulations, or presence of violence implies high discount rates. Low discount rates under strong governance reflect effective institutional and organizational performance. In the fourth scenario, representing fragmented governance between developed countries and developing countries, OECD countries in EUR, NAM and PAO are assumed to have strong governance, whereas other countries have weak governance. Discount rates remain the same as in the reference for all the scenarios until 2010 and then change to scenario values from 2015.

2.4 Results

2.4.1 Influence of governance performance on land-use change

In general, cropland area is increasing over time due to a growing population and food demand in all four scenarios, but the growth rates are different. Strong governance leads to lower cropland expansion mainly due to moderate cropland expansion rates in LAM, FSU, SAS, AFR and PAS. Weak governance and fragmented governance result in a large area of additional cropland (Fig. 2-1). If governance performance can be improved from the *status quo* to strong governance, 302.4 million hectares of cropland expansion could be avoided in 2045. In contrast, 151.0 million hectares of cropland may be converted in 2045 if the current governance performance regresses to weak governance.

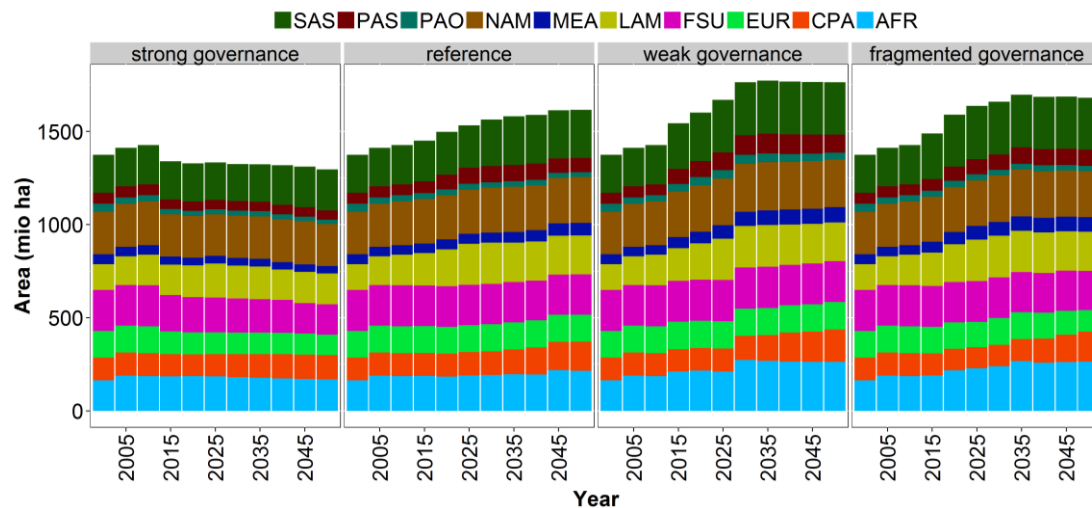


Fig. 2-1. Regional cropland expansion over time in each scenario.

Cropland expansion mainly happens in the regions which have large endowments of forest, particularly tropical forest (Fig. 2-2). These regions, e.g., AFR, PAS and LAM, are often characterized by unstable political and economic conditions. We find that in particular these regions have higher average yield increase under improved governance performance (Fig. A-4 in Appendix A). For instance, in LAM and PAS the land-use intensity in 2045 under strong governance is 36.3% and 47.5% higher, respectively, than under weak governance. The same land-use intensity pattern is observed for other regions except PAO, in which land-use intensity is lower in the strong governance scenario than that in the reference scenario.

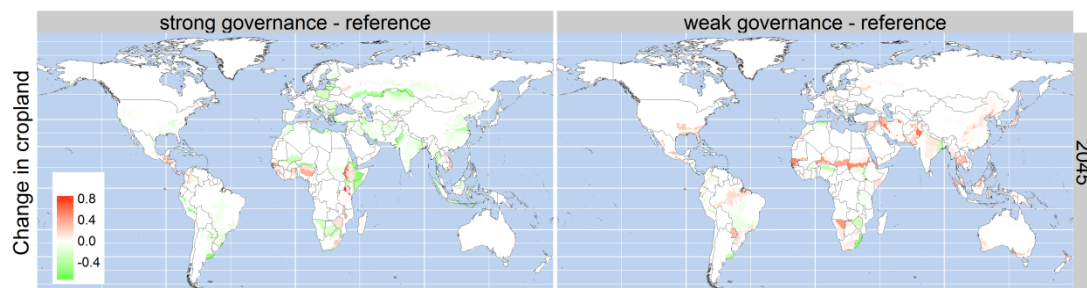


Fig. 2-2. Change in cropland in cells (0.5 degree) between strong and reference governance scenario (left) and between weak governance scenario and reference (right) in 2045.

Agricultural R&D investments in the model are heavily influenced by governance performance, which in turn affect yield increase. If governance performance is weak, low yield levels have to be compensated by expanding cropland. Instead of relying on cropland expansion to fulfill food and material demand, strong governance stimulates yield increases by investing in agricultural technologies. Between 2010 and 2045, strong governance leads to 51.3% increase in average yields, measured as land-use intensity, and by contrast the land-use intensity increases by 30.8% in the weak governance scenario (Fig. 2-3). In the fragmented governance

scenario, the land-use intensity is slightly higher than under weak governance and the reference scenario, which is mainly due to large yield increases in NAM caused by low discount rates in developed countries and high discount rates in developing countries (Fig. A-1 in Appendix A).

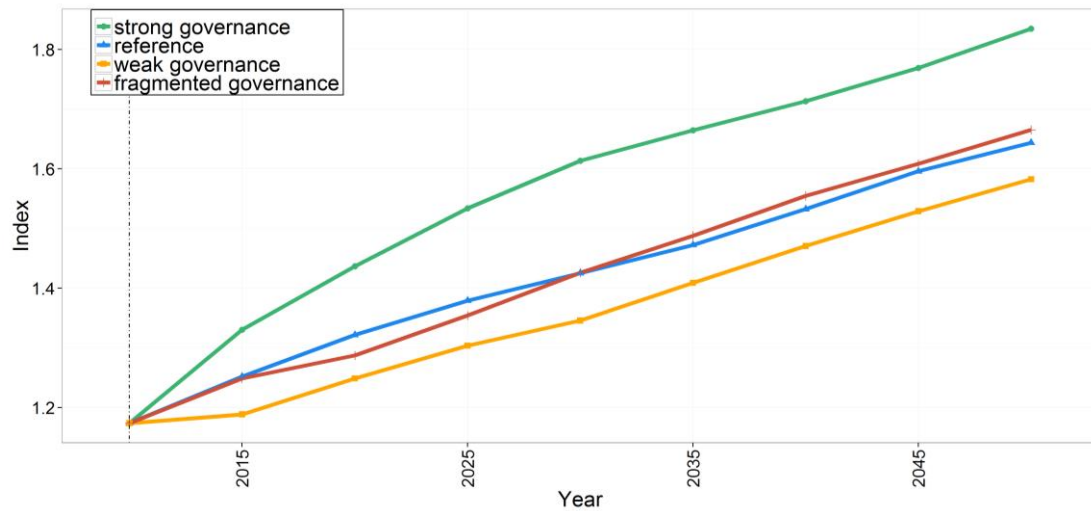


Fig. 2-3. Land use intensity over time in the four different scenarios w.r.t. 2010.

With weak governance leading to increases in discount rates for investment, the annuity factor decreases and the annuity-related costs of technological change and cropland conversion increase. The increase in annuity-related technological costs is higher, compared to cropland conversion costs. Therefore, to fulfill global food demand at minimum costs, the model relies more on cropland expansion rather than on improving yields. One devastating consequence of rapid cropland expansion and slow agricultural technological progress is deforestation. Although forest area decreases over time in all scenarios, it shrinks much more when associated with an increase in cropland and grassland within the weak governance scenario (Fig. 2-4). By contrast, the pace of deforestation could be restrained by strong governance. Assuming governance performance is improved from the *status quo* to strong performance, 195.8 million hectares of deforestation can be avoided by 2045, whereas the difference from the weak governance scenario to the reference scenario amounts to an additional 95.8 million hectares of deforestation. Deforestation increases carbon emissions, and thus the model shows that emissions increase correspondingly (Fig. A-5 and Fig. A-6 in Appendix A). Improving governance may restrain a large amount of carbon emissions, especially in LAM and AFR.

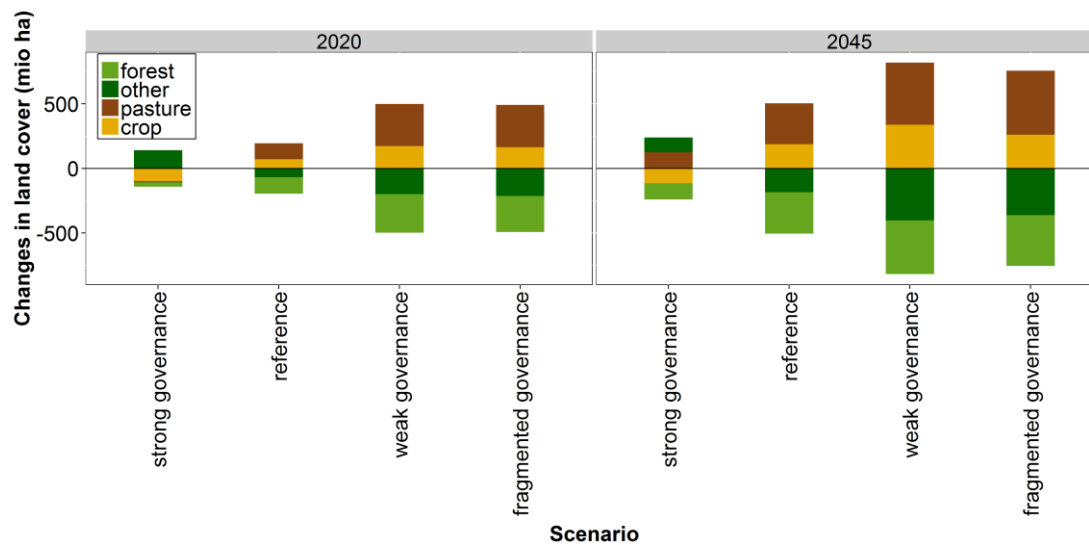


Fig. 2-4. Change in global land cover in different time steps for each governance scenario w.r.t. 2010.

2.4.2 Impacts of governance on food prices

Governance performance affects not only land-use patterns but also food prices. Cereals, sugar crops, oil crops, and livestock products are among the important commodities used as the basis for computing the food price index in this study. The food price index is calculated as a measure of the scarcity of the resources used for food production. Fig. 2-5 indicates that by improving governance performance, prices of cereals including rice and of oil crops can be maintained at a relatively low level.

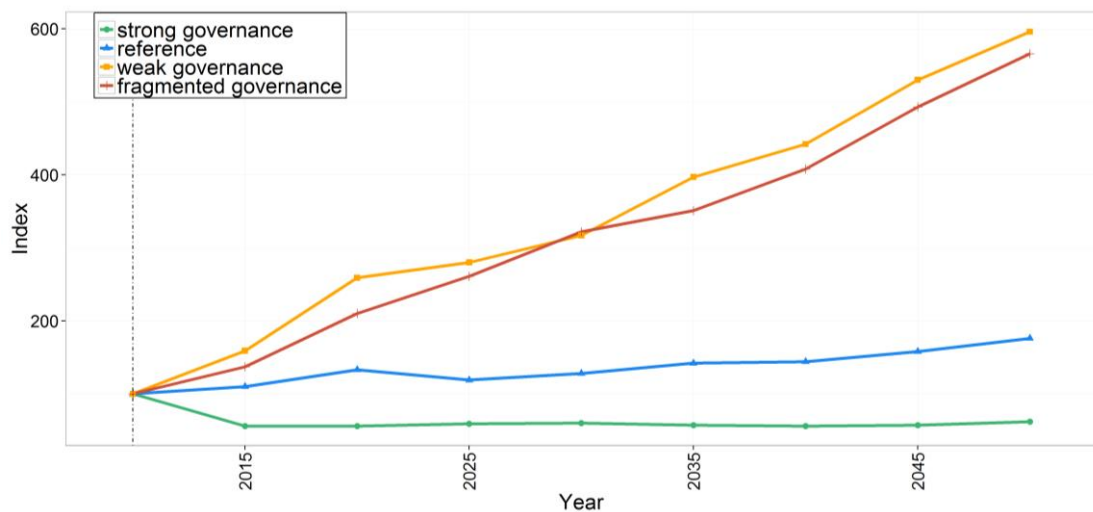


Fig. 2-5. Change of global food price index over time in each scenario w.r.t. 2010.

Comparing food prices between 2010 and 2045, strong governance may decrease global food prices by about 43%, while it could quadruple, compared to the food price of the base year, if the governance performance is weak or fragmented. Food prices differ strongly between

strong and weak governance scenarios for developing regions, e.g., AFR, SAS, and LAM (Tab. A-1 in Appendix A). Between 2010 and 2045 in the weak governance scenario, food prices increase by more than quadruple in these regions. By contrast, with strong governance performance, food prices by 2045 decrease by 56% and 32% respectively in AFR and SAS.

2.4.3 Impacts of governance on agricultural trade balances

Trade balances are simulated as net exports. We focus on the most important commodities, i.e., cereals and oil crops, since maize, rice, and wheat that are the most important food crops and provide at least 30% of food calories to more than 4.5 billion people in 94 developing countries (Shiferaw et al., 2011). Oil crops, e.g., soybeans, oil palm, and rapeseeds, also play an important role in human nutrition, as they are used in large quantities either directly as food or indirectly as animal feed, food processing, or cooking oils (Bressani, 1981; Jacobs et al., 2011; Keatinge et al., 2011; Choi et al., 2013).

In the reference scenario, NAM and CPA dominate the exports of cereals including rice. CPA will become a major exporter of cereals in 2035 and overtakes NAM as the largest exporter in 2045. On the import side, starting from 2040 AFR increases imports and becomes the largest importer in 2050. Trade balances of cereals for Africa in the strong governance scenario differ greatly from the other three scenarios. AFR gradually reduces imports of cereals in the strong governance scenario, with NAM and CAP being the major exporters of cereals. Net exports of temperate cereals in AFR in 2050 amount to around 8.7 million tons of dry matter (Fig. 2-6).

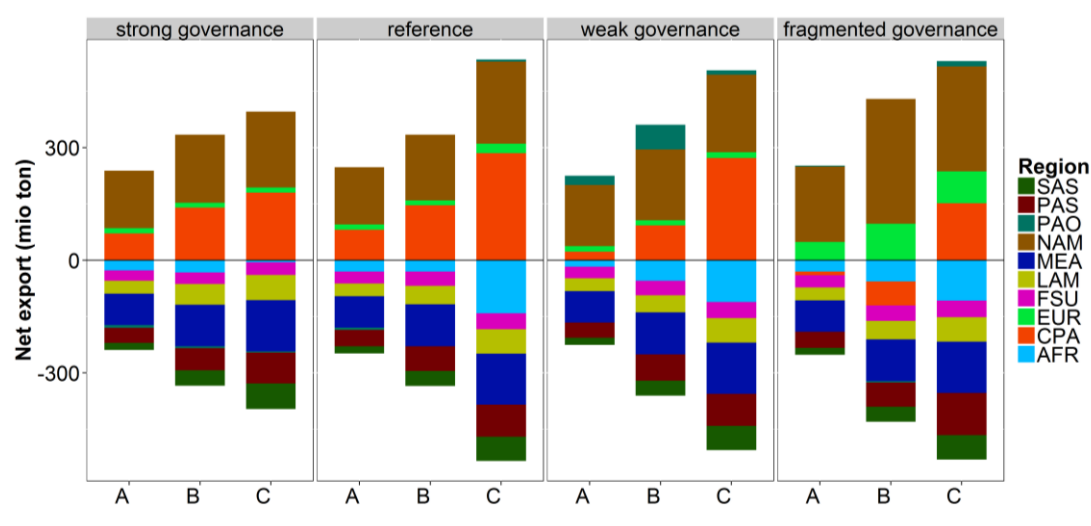


Fig. 2-6. Average of net exports of cereals over time in each scenario for three time-spans (A = 2010-2020; B = 2025-2035; C = 2040-2050).

The export trade market of oil crops is dominated by NAM and LAM in the reference scenario, although CPA rises as an exporter later on because of its comparative advantage in producing soybeans. On the import side, until 2035 CPA imports the largest amount of oil crops. SAS,

AFR and MEA gradually increase their imports, and become the major importers in the last period. Comparing net exports of oil crops between strong and weak governance scenarios, AFR shows larger amount of imports, while NAM remains the biggest exporter of oil crops (See Fig. A-7 in Appendix A).

2.5 Discussions

2.5.1 Importance of governance performance for deforestation and yield increase

It is observed that productivity growth rate is declining, but this does not imply the productivity is facing an upper limit, because it is due to a decrease of R&D investment (Alston et al., 2009; Alston, 2018). The difficulty for further increasing crop yields due to TC is reflected by the increasing yield-investment ratio, which is driven by increasing land use intensity. In the model-based scenarios, most regions under the reference scenario follow the historical trends in productivity growth (Fig.A-4 in Appendix A). The research findings at the global level suggest that improved governance performance lowers deforestation as a result of reducing cropland expansion and increasing crop yields. Differences in cropland expansion and deforestation between the different governance scenarios mainly occur in regions which have a relatively weak governance *status quo*, such as Sub-Saharan Africa, Latin America, and Southeast Asia. The difference in agricultural technological progress between the governance scenarios is especially high in these regions, because cropland expansion dominates over R&D investments in the weak governance scenario. These regions often have a rich endowment with forest resources. For instance, there are around 721 million hectares of forests in Africa, and 1023 million hectares in Latin America (FAO, 2018). Agricultural production, especially in Africa and Asia, is not very capital-intensive (Bohn and Deacon, 2000), as smallholder farming systems are prevalent which strongly rely on labor input (Salami et al., 2010; FAO, 2010; Takeshima et al., 2013). Hence, capital investment in production can be easily substituted by increasing cropland and labor. There exists an intensive debate about potential rebound effects, that is, whether improving governance will lead to even more deforestation (Liscow, 2013; Ceddia et al., 2014). The presented research shows that improving governance could avoid deforestation at the global scale, partly because the cost minimization model assumes the substitution between TC and cropland, while analyses in support of the rebound effect usually assume a complementary relationship between TC and cropland. Technological investment is less favored within the weak governance scenario, since insecure land tenure makes investment in the future more risky. Hence, cropland area expands to increase production, and forests are the major source for newly converted cropland. In contrast, strong governance leads to well-defined and enforced property rights. It reduces the risks associated with investment and stimulates incentives for R&D investment in agriculture. Strong governance performance reinforces land-use regulations, which could conserve most of the forest (Nepstad et al., 2002; Soares-Filho et al., 2014; Nepstad et al., 2014). The recent

development and extension of the Soy Moratorium in Brazil is an example of a strong national policy, succeeding in curbing the expansion of soy production and consequentially deforestation (Gibbs et al., 2015).

Governance performance has significant impacts on adoption of agricultural technologies, because it affects risks and uncertainties associated with investments and therefore affects the attractiveness of agricultural technologies to decision makers. In the model, Sub-Saharan Africa in 2010 has the same land-use intensities in the strong governance as in the weak governance scenarios. Results show that until 2045, there is higher increase in average yields in the strong governance scenario and the costs of technological investments the model considers during optimization differ a lot. In fact they are almost four times as high in the weak governance scenario as in the strong one due to the accounting of risks (Tab. 2-2). But if considering the technological investment costs *per se* without accounting for risks, fewer investments are actually made in the weak governance scenario, compared to the investments made in the strong governance scenario. Looking at the risk associated with average investments in South Asia (incl. India) and Sub-Saharan Africa in the reference scenario, similar patterns are found. They have similar land-use intensities in 2010, but South Asia shows stronger governance performance than Africa in, e.g., accountability and rule of law. There is a similar increase in average yields in the two regions until 2025, but the risk-accounting costs of technological change differ a lot, being five times as higher in Africa than in South Asia.

Tab. 2-2. Change of average yields due to land-use intensity and related costs in AFR in the strong governance and weak governance scenarios.

Scenarios	τ 2010	τ 2045	$\Delta \tau$	Annuity costs of technological investments per unit of production (unit: USD/ton dry matter)*	Total costs of technological investments per unit of production (unit: USD/ton dry matter)**
Weak governance	0.75	1.73	0.88	3033.11	133.20
Strong governance	0.75	1.94	1.19	85.57	169.81

Note: $\Delta \tau$ refers to the difference of land-use intensity due to technological change. * refers to the average annuity TC costs between 2010 and 2045 (which consider risk due to the annuity approach); **refers to average total TC costs without accounting for risks between 2010 and 2045.

Some countries might already have good governance, but it makes a decisive difference in the level of investment made in increasing productivity in developing countries. Developing countries, e.g., Sub-Saharan Africa, gain more from the improvement of governance performance than developed countries (Tab. 2-3). Growth rates of average yields in Sub-Saharan Africa, due to improvement of governance, range from 0.17 to 0.34 in the period

between 2015 and 2040, which is higher than the growth rate of average yields in North America.

Tab. 2-3. Difference in average yield attributed to land-use intensity increase due to governance improvement between Africa and North America.

Year	2015	2020	2025	2030	2035	2040
$\Delta\tau_{NAM}$	0.13	0.11	0.09	0.1	0.09	0.06
$\Delta\tau_{AFR}$	0.17	0.22	0.27	0.34	0.23	0.21
$\Delta\tau_{AFR-NAM}$	0.04	0.1	0.18	0.23	0.14	0.14

Note: $\Delta\tau$ refers to the difference of land-use intensity index between strong governance and weak governance scenarios.

2.5.2 Importance of governance performance for poverty reduction

Impacts of food prices on poverty depend on the combined effects on consumers and producers, because increasing food prices reduces the real income of those consuming food but raises the real income of producers. However, increasing food prices usually cause poverty rates to increase (Ivanic and Martin, 2008). Anderson et al.(2013) argue that the rise of food prices in the period between 2006 and 2008 caused 80 million people to fall into poverty. It is estimated that up to 325 million extremely poor people will live on under 2 USD per day in 2030, the majority of them in South Asia and Sub-Saharan Africa, due to declining yields and increasing food prices caused by climate extremes (Shepherd et al., 2013).

If there is a substantial share of food imported into a country, the negative impact on consumers is larger than the positive impact on net producers of locally produced foods (Wodon et al., 2008). Looking at the food price index and trade patterns of cereals in different governance scenarios for the period between 2020 and 2050 in the model, I find that Sub-Saharan Africa and South Asia are net importers in the weak governance scenario and global food prices are higher than in the strong governance scenario. Food prices in Sub-Saharan Africa are more than ten times higher in the weak governance scenario than in the strong governance scenario and four times higher in South Asia. Because countries in Africa and Southeast Asia are net importers of temperate cereals, it could be expected that weak governance causing high food prices will tend to result in higher poverty, even if some local producers will benefit. Because these two regions, in general, exhibit low income levels but a high share of income being spent on food expenditure, the increase in food prices caused by weak governance will not only raise poverty rates but most hurt who are already poor. The impact of food prices on the poor in urban areas is often more dramatic than on the poor in rural areas, since urban households are more likely to be net consumers of food (Wodon et al., 2008). Thus, high food prices caused by weak governance may lead to higher poverty in urban areas in developing countries, particularly in Latin America where a large proportion of poor people live in urban areas. In a fragmented scenario with strong governance in

developed regions and weak governance in developing regions, I find even higher food prices compared to the weak governance scenario. There are large shifts in Europe's trade balance of cereals, due to high yield increase driven by strong TC in the developed regions and low yield increase in the developing world. The results are due to the global optimization of production.

In the model results, high average yields are associated with low food prices when the governance performance is strong. Because food prices are affected by supply and demand of food products, productivity growth, as the primary driver for the long-term increase of agricultural production, could heavily influence the prices by increasing the supply (Alston et al., 2009; Alston and Pardey, 2014). Conversely, weak governance performance leads to low yields and high food prices, as well as cropland expansion. Simple expansion of cropland into unproductive land not only results in increasing deforestation but also increases food prices which affect peoples' livelihoods, especially for those who are net consumers in developing countries.

2.6 Conclusion

The study employs a global agro-economic optimization dynamic model to analyze the impacts of governance performance on land-use dynamics and food prices. Since it is difficult to include governance indicators directly into numerical models, the study uses lending interest rates as discount rates to reflect risk-accounting factors associated with different governance scenarios. In the model results, I find that weak governance may lead to very high deforestation and cropland expansion, which mainly happens in developing countries in Latin America, Sub-Saharan Africa, South Asia, and Southeast Asia. By contrast, strong governance performance provides stable political and economic conditions, which may bring down discount rates and stimulate investment in agricultural technologies. Strong governance makes a decisive difference in the level of investment made in increasing productivity in developing countries. Developing countries, e.g., in Sub-Saharan Africa, gain more from the improvement of governance performance than developed countries. Improving governance performance can enforce forest protection as well as induce fairly strong decreases in food prices by increasing yields. In particular in developing countries in Sub-Saharan Africa and South Asia, with persistent poverty issues and rich endowments of forest resources, strong governance performance is expected to slow the pace of deforestation and contribute to poverty reduction.

There are several caveats to the findings. Firstly, I assume constant governance performance over time in each scenario and use constant discount rates to represent it in the analysis without accounting for institutional dynamics. However, the change of governance performance may be slow and path dependent (North, 1993). Secondly, interest rates are proved to be good proxy for governance performance in the studies related to resource

depletion (Deacon, 1999, 1994; Bohn and Deacon, 2000; Ferreira and Vincent, 2010). It is worth noticing that interest rates are often affected by monetary policy, which might not be able to reflect the exact governance performance. Finally, I do not consider the upper limits of yield growth driven by technological change, but the difficulty for further increasing crop yields is reflected by the increasing yield-investment ratios. It implies that achieving one additional unit increase of yield increase in a subsequent time step is more expensive than in the previous steps (Dietrich et al., 2012, 2014).

3 BEYOND LAND-USE INTENSITY: ASSESSING FUTURE POTENTIAL OF GLOBAL CROP PRODUCTIVITY GROWTH UNDER DIFFERENT SOCIOECONOMIC PATHWAYS

Abstract

This study uses a two-step approach to understand long-term productivity changes in the crop sector at global and regional levels, firstly by employing a global agro-economic dynamic optimization model to simulate endogenous land-use intensity growth under future socioeconomic scenarios, and then by applying a non-parametric estimation method to estimate regional and global total factor productivity changes. It does not only enable the projection of land productivity changes induced by endogenous technical change and land expansion but also provide a basis for estimating total factor productivity changes. The results suggest that global productivity growth is likely to continue. However, the growth rates vary among different socioeconomic conditions and different productivity indices. The fast growth of total factor and partial factor productivity can be reached when slow population growth and high economic growth entail moderate food demand and low investment risks. In contrast, high population and low economic growth could lead to relatively high land-use intensity due to the extreme pressure on agricultural production, however, matched with low total factor productivity growth. The study shows that it is crucial to consider economic and demographic structure changes under different socioeconomic conditions when projecting future productivity changes. Differences in socioeconomic conditions lead to a spread in total factor productivity growth in the crop sector, which has profound implications for cropland expansion and food prices. Total factor productivity growth is likely to reduce further cropland expansion and to limit increases in food prices.

Keywords: endogenous technical change, productivity growth, land-use intensification, cropland expansion, and shared socioeconomic pathways

3.1 Introduction

Agricultural development is essential in the broader development context, exerting impacts not only on poverty reduction and food security but also on ecosystems (Barrett et al., 2010; Sayer and Cassman, 2013; Wang et al., 2016). Increasing output in the agricultural sector in the past mainly depended on land expansion (Hansen and Prescott, 2002). It is estimated that the global cropland area and grassland area increased by about 1500 million hectares and 2600 million hectares, respectively, in the past three centuries (Lambin et al., 2003). Although the pace of land expansion has been lower in the past decades, and a significant decoupling between food production increase and cropland expansion has occurred after 1960 (Lambin et al., 2003), land expansion is still taking place, some of which is on plots with high ecological values. Overall, 83% of all newly converted agricultural land between the 1980s and 2000s was formerly tropical forest (Gibbs et al., 2010), and deforestation contributed to 12–20% of global anthropogenic carbon emissions in the last two decades (van der Werf et al., 2009). The exact amount of land needed for agricultural production varies, depending on the state of the applied agricultural technology and land quality (Lotze-Campen et al., 2010; Wang et al., 2016). For instance, technological progress associated with the green revolution successfully increased crop yields without a corresponding expansion of cropland to meet the increasing food needs of Asia's growing population (Sayer and Cassman, 2013).

To meet future agricultural demand, technological progress in the agricultural sector has become more critical than ever (Wiebe et al., 2003; Tester and Langridge, 2010). The essential role of technologies in promoting agricultural productivity and inclusive economic growth is widely recognized (Barrett et al., 2010), and the intrinsic properties of TC are extensively studied in the discipline of economics (Arrow, 1962; Romer, 1986; Lucas, 1988; Romer, 1990). In contrast to the assumption about exogenous TC in the early neoclassical growth theory (Solow, 1957), TC is found to be an endogenous process (Arrow, 1962; Lucas, 1988; Romer, 1990). In the agricultural sector, TC can occur through the adoption of new crop varieties, management improvements, and expansion of irrigation infrastructures (Griliches, 1957; Lin, 1991; Schneider et al., 2011; Baker et al., 2012). Advancing agricultural technology is generally triggered by investment in R&D (Griliches, 1963) and can be associated with population pressure (Boserup, 1975), while the underlying driving forces for advancing agricultural technology is changes in relative resource endowments and factor prices (Ruttan, 2002). The importance of endogeneity of TC is recognized by modelers, but assume exogenously due to limited data. To study the impacts of productivity changes on land use changes and food security, existing economic models often treat productivity changes as parameters, either as a shifter in crop yields in partial equilibrium models, or changes of productivity factors in a production function in general equilibrium models (Hertel et al., 2016). A few exceptional, such as MAGPIE, LINKAGE, assumes endogenous TC (van der Mensbrugghe, 2005; Dietrich et al., 2014).

Moreover, different methods have been employed to improve productivity measures (Alston, 2018). The methodological differences reflect conceptual differences between PFP and TFP. Productivity measured as PFP (Wiebe et al., 2003; Rozelle and Swinnen, 2004; Verburg et al., 2008; Havlík et al., 2013), is informative to understand underlying factors of productivity changes but can be misleading since not all production inputs are taken into account. For instance, higher crop yields may be driven by more fertilizer use or higher labor input. Hence, despite increased land productivity, overall productivity might remain constant or even deteriorate. In contrast to PFP measures, TFP provides a holistic measure of productivity growth attributed to all input factors (Ludena et al., 2007; Fuglie, 2008). Social accounting approach (Fuglie, 2008; Solow, 1957) or econometric techniques (Ludena et al., 2007) can be used to estimate TFP changes. However, there is seldom prediction of TFP, due to uncertainty in the future, although it is equally important to have (Hertel et al., 2016). Exceptionally, Ludena et al. (2007) provide forecasts of TFP, based on the assumptions of trends in technical changes and extrapolations of efficiency changes using the estimates from logistic regressions. The prediction relies on information of limited time series data, without considering possible structural changes in the future, such as changes in food demand, demography and biofuel demand, which could potentially understate the changes in productivity.

To bridge the gap and to improve understanding of productivity changes under future socioeconomic conditions, this study employs a two-step approach to project long-term future productivity changes in the crop sector at global and regional levels until 2050. This approach does not only enable the projection of endogenous PFP changes induced by TC and land expansion but also provide a basis for estimating TFP. In the first step, it employs MAgPIE to simulate endogenous land-use intensity growth in the crop sector under different future socioeconomic scenarios. In the second step, the study applies a non-parametric estimation method to estimate TFP changes with the MPI based on simulated crop production to further complement the analysis.

The remainder of the article is organized as follows. Section 3.2 introduces the methods for computing multiple productivity indicators. Section 3.3 shortly describes scenarios based on Shared Socioeconomic Pathways (SSPs) and the representation of major features of the modeling framework. Results about projections of land productivity and TFP growth at global and regional levels in the SSPs are presented and discussed in Section 3.4. Section 3.5 draws conclusion.

3.2 Methods

The study combines the quantitative economic modeling approach with non-parametric estimation methods to project future productivity changes under different future socioeconomic conditions. Projections depending on endogenous technological change dynamics avoid underestimation of the adaptability, especially in the long run (Dietrich et al.,

2014). TC is implemented based on a measure for agricultural land-use intensity, which is a surrogate representing human-induced productivity through activities such as R&D, infrastructure development and management but excluding productivity changes due to changes in biophysical conditions (Dietrich et al., 2012, 2014).

3.2.1 Computing productivity indices beyond the land-use intensity

The endogenous implementation of TC provides a projection for land-use intensity, $x_{i,\theta}^{tc}$, as defined in equation (2.2) in Chapter 2. It is an output-oriented measure for land productivity, representing the increase of yields due to a potential suite of changes in management and technological advances without considering biophysical characteristics (Dietrich et al., 2014).

Additional to the land-use intensity measure, average yields are computed to represent another form of land productivity as described in equation (3.1) and can be decomposed as a product of cumulative land-use intensity in $f_{i,t}^{growth}(\cdot)$, and a weighted mean of observed yields for the initial period, $p_{j,k,w}^{ref\ yield}$, with weights $\omega_{j,t,k,w}$. To keep it simple, climate impacts on yields are excluded in the study, and therefore initial biophysical yield potential remains constant over time. The initial yields represent the land quality, which is determined by water availability and other biophysical conditions, simulated by LPJmL. Increasing land-use intensity will raise the average yields, as stated in the Proposition B.1 (Appendix B). Because initial yields vary among different spatial units and between different irrigation types of cropland, cropland expansion can lead to an increase or decrease of average yields (Proposition B.2 in Appendix B). It indicates the yield increase driven by land-use intensity growth as well as cropland expansion involving heterogeneous land quality that depends on attributes of cropland, such as water availability for irrigation.

$$\begin{aligned}
 x_{i,t}^{yield} &= \frac{\sum_k x_{i,t,k}^{production}}{\sum_k x_{i,t,k}^{area}} \\
 &= f_{i,t}^{growth}(\cdot) \sum_k \sum_{j_i} \sum_w \omega_{j,t,k,w} p_{j,k,w}^{ref\ yield} \\
 , \text{ where } \omega_{j,t,k,w} &= \frac{x_{j,t,k,w}^{area}}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}}
 \end{aligned} \tag{3.1}$$

While land-use intensity and yield index are PFP measures focusing on a specific input (in this case land), TFP measures the changes of productivity accounting for all the inputs. In this study, TFP change is estimated as an (output oriented) MPI, which is based on the estimate of the Shephard output distance function using the DEA method to construct a piece-wise linear production frontier for each year in the sample (Färe et al., 1994; Nin et al., 2003; Coelli and Rao, 2005). It treats the aggregated amount of crop commodities as outputs, y , and cropland area, production factors and used water amount as inputs, x_n . The distance

function² is $D_o(x, y) = (\sup\{\theta: (x, \theta y) \in S\})^{-1}$, in which S denotes production technology transforming inputs $x \in R_+^N$ into possible outputs $y \in R_+^M$: $S = \{(x, y) \text{ such that } x \text{ can produce } y\}$, and θ is the coefficient dividing y to get a frontier production vector given x (Nin et al., 2003). The MPI is estimated as a geometric mean of two Malmquist matrixes, by solving linear-programming problems to get estimations of four types of distance functions³ (Färe et al., 1994).

$$\begin{aligned}
 (D_\psi(x_{ii,\phi}, y_{ii,\phi}))^{-1} &= \max \theta_{ii} \\
 \text{s. t.} \\
 \theta_{ii} y_{ii,\phi,n} &\leq \sum_{i=1}^I z_{i,\psi} y_{i,\phi,n} \\
 \sum_{i=1}^I z_{i,\psi} x_{i,\phi,m} &\leq x_{ii,\phi,m} \\
 z_{i,\phi} &\geq 0 \\
 \psi, \phi &= s, t
 \end{aligned} \tag{3.2}$$

, where $i, ii \in \{1, \dots, I\}; I = 10; t \in \{1, \dots, T\}; T = 11; x_{i,\phi,m}$ refers to m inputs and $y_{i,\phi,n}$ is n outputs. In the presented analysis, $M = 3$ includes production factor requirement costs (a package of capital, labor and fertilizer costs in MAgPIE), cropland area and amounts of used water for irrigation. $N = 1$, refers to aggregated crop production; $z_{i,\psi}$ are weights applied to both input and output in time ψ . By assuming constant return to scale, the study does not put the constraint of a convex combination on weights in the equations.

The MPI then is calculated as,

$$M(x_{t+1}, y_{t+1}, x_t, y_t) = \frac{D_{t+1}(x_{t+1}, y_{t+1})}{D_t(x_t, y_t)} \left[\frac{D_t(x_{t+1}, y_{t+1})}{D_{t+1}(x_{t+1}, y_{t+1})} \frac{D_t(x_t, y_t)}{D_{t+1}(x_t, y_t)} \right]^{\frac{1}{2}} \tag{3.3}$$

TFP change can be decomposed into the shift of technology (i.e., technical change, the part inside the square brackets, estimated as a geometric mean of technological shifts evaluated at t and $t + 1$ and catch-up to the frontier (the part outside the square bracket) (Färe et al., 1994). The latter one refers to the gaps between observed production and maximum potential production for the two time steps, representing that regions converge toward the long-term production frontier. The long term production frontier is SSP-specific but is assumed to be common for all the regions in a single SSP. For overcoming the dimensionality problem (Coelli and Rao, 2005), various crops are aggregated into one single output for the estimation of MPI. Different from constructing land quality indicators based on shares of irrigated land to correct biases in the analysis of TFP (Craig et al., 1997; Wiebe et al., 2003;

² It is identical to $D_o(x, y) = \inf\{\theta: (x, y/\theta) \in S\}$.

³ $D_t(x_t, y_t)$ is a column vector of distance function for all the regions, e.g., $D_t(x_t, y_t) = (D_{1,t}(x_{1,t}, y_{1,t}), \dots, D_{I,t}(x_{I,t}, y_{I,t}))$. The notation in the distance functions and MPI is in line with Färe et al., 1994, but slightly differs from that in the other indices. x refers to input and y is output. The specification should be clear in the context.

Fuglie, 2008), I estimate the MPI in this study by considering the water amount directly as an input, which represents land quality adjusted with weights for irrigated and rain-fed cropland.

Estimating global MPI directly for each SSP is often infeasible, because the linear programming problems for the estimation cannot be solved. To overcome this problem, studies often incorporate global data directly into regional data (Ludena et al., 2007), but this approach violates certain assumptions of DEA, such as a common production frontier (Dyson et al., 2001). A more theoretically sound way to compute global MPI is constructing a weighted average index based on the distance functions estimated from the regional data with appropriate weighting (Färe and Zelenyuk, 2003; Coelli and Rao, 2005). The aggregation scheme in the study is adopted according to the method derived by Färe and Zelenyuk (2003) and Zelenyuk (2006) based on production duality (See details in Appendix B). Similarly to the regional MPI, the global MPI can also be decomposed into shift of the production frontier and catch-up to the frontier.

3.2.2 Scenarios

In the future, the world will encounter more interconnecting challenges. As the global population continues to grow, intertwined with higher purchasing power, especially in developing and emerging countries, increasing demand for crops and livestock products can be anticipated (Bodirsky et al., 2015). Since demand strongly depends on uncertain trends such as population and economic growth, it is unclear how the demand for agricultural goods will evolve, and it is uncertain how land dynamics, especially productivity patterns, will respond to the future demand. The recently developed SSP framework depicting plausible future changes in demographics economy, technology, and environment (O'Neill et al., 2017; Riahi et al., 2017) will be used to construct five different scenarios for the analysis. Different assumptions of SSPs about stylized indicators are shortly introduced as follows:

- SSP1 (Sustainability): A sustainable development world with low population growth and high per-capita income while reducing global inequalities. These developments go hand in hand with high education and fast technological progress, also in the agricultural sector. Lifestyles are sustainable and environmental legislation progressive.
- SSP2 (Middle of the road): A middle of the road scenario being business as usual, keeping the currently observed trends.
- SSP3 (Fragmentation): A fragmented world with limited cooperation between regions leads to reduced trade flows, slow technological change and development in combination with a fast growing population; investments in human capital are low, institutional development is unfavorable.
- SSP4 (Inequality): A separate and unequal world in which there is rapid technological

development and economic growth in developed regions, while some of the least-developed regions become disconnected from progress in the remaining world and face high population growth, poor governance as well as low economic growth.

- SSP5 (Conventional development): A world in which rapid and globalized economic growth is based on rapid technological progress, free trade, and conventional carbon-intensive development. Living standards are high throughout the world and go along with high energy consumption, and dietary patterns which are characterized by high per-capita demand, in particular for animal-based products. Institutional stability allows for a favorable investment environment.

The qualitative storylines of the SSPs (O'Neill et al., 2017) as well as quantitative population (Kc and Lutz, 2017) and income scenarios (Dellink et al., 2017) are used to parameterize the MAgPIE model, e.g., in respect to trends in trade liberalization, environmental restrictions and costs of technological change (Tab.B-1 in Appendix B). Population and income scenarios of the SSPs are translated into demand for crop and livestock products, while different trajectories of economic development influence dietary preferences such as meat consumption share, amount of calories consumed or wasted per person. The SSP indicator “environment” is implemented in the model through protection levels of ecosystems, such as forests. “Technology” in MAgPIE is parameterized as soil nitrogen uptake efficiency and livestock efficiency (the amount of feed needed to produce a certain amount of livestock products) but leaving crop productivity changes to be determined endogenously in the optimization. Implementing trade liberalization based on different self-sufficiency rates in the model represents the dimension of “globalization” of the SSP storylines. By following the narratives about institutional quality, I include risk-accounting factors to represent political stability and governance performance in SSPs, which affects investments risks and uncertainties through different discount rates. High investment risks reduce capital investments in agricultural production and encourage cropland expansion (Deacon, 1994, 1999; Bohn and Deacon, 2000). We, therefore, use annual interest rates as discount rates, based on a literature range of 4–12% (IPCC, 2007), as a proxy for risk-accounting factors associated with governance performance (Wang et al., 2016).

3.3 Results and discussions

3.3.1 Land productivity growth under SSPs

Land productivity is measured as PFP by both land-use intensity and yield index, with land-use intensity referring to homogenous land quality and yield index encompassing heterogeneous land quality. Until 2050, global land-use intensity increases by 94.8% and 77.3% under SSP5 and SSP1, respectively (Fig. 3-1). SSP3 also shows a relatively strong increase in

land-use intensity by 74.2%, while SSP2 and SSP4 experience relatively low land-use intensity growth, 60.8% and 45.9%, respectively.



Fig. 3-1. Global land-use intensity (left panel) and yield index (right panel) for each SSP by 2050.

The land-use intensity in the model is mainly affected by two factors, namely, risks associated with investment and pressure from increasing crop demand. Investment risks and uncertainties associated with investments, determining the attractiveness of agricultural technologies, are influenced by the institutional environment (Deacon, 1994, 1999; Bohn and Deacon, 2000; Deininger et al., 2014; Wang et al., 2016). In particular, Wang et al. (2016) analyze the impacts of governance performance on the growth of land-use intensity by using the MAGPIE model to simulate different governance performance scenarios and controlling for other important variables, such as food demand. They find that land-use intensity increases when governance performance is strong. Following the same logic, SSP5 and SSP1 are characterized by fast economic growth and a stable institutional environment resulting in fast technological progress and high land-use intensity. This leads to a deceleration of cropland expansion in these two scenarios, as increasing demand is mainly satisfied by intensified production and yield improvements resulting from technological investments. In contrast, there is more cropland expansion in SSP2, SSP3, and SSP4 than in SSP1/SSP5. The difference in global land-use intensity between SSP2 and SSP4 reflects that relatively strong governance with low risks in developed regions (NAM, EUR, and PAO) does not necessarily lead to the globally higher land-use intensity growth in SSP4, compared to SSP2, since developing regions in SSP4, such as AFR, MEA and SAS, experience weaker governance with high discount rates (Appendix B).

Pressure from the demand side is another key factor driving land-use intensity. As shown in Fig. 3-1, the global land-use intensity in SSP3 is 13.4% higher than in SSP2 in 2050 and close to SSP1, despite lower investment risks in SSP1 and SSP2. This is due to high population

growth increasing demand for crop products and limited opportunities to international trade in SSP3 (Appendix B). Thus, technological progress as an endogenous response mechanism is the last resort for increasing land-use intensity as fertile land is already converted into cropland. This is specifically true for the developing regions, such as AFR, MEA, and SAS, which have very high population growth in SSP3, and therefore even higher land-use intensity increase than in the developed regions (Fig. B-1 in Appendix B). In this scenario it is arguable whether the projected increase in per-capita demand can actually be realized, as high prices would lead to reduced demand, including a higher degree of undernourishment.

The yield index, i.e., average yield change, also indicates continuous growth of global land productivity over time for all SSPs (Fig. 3-1). By 2050, SSP1 has the highest average yields, more than twice as high as in 1995, followed by SSP5 (124.9%) and SSP2 (93.1%). SSP3 and SSP4 have the lowest growth rates in average yields with 83.0% and 78.1%, respectively. Since the yield index is a weighted measure, model results indicate that the average yield is driven by cropland expansion into areas with different agricultural suitability as well as land-use intensity growth. For instance, in SSP1 that is featured with low investment risks and population pressure with globalized international trade, modest cropland expansion, and high land-use intensity leads to high average yields and vice versa for SSP3. Cropland expansion affects average yields through the initial yields of newly converted cropland, which is mainly dependent on irrigation conditions. From 1995 to 2050, the share of irrigated area in SSP1, SSP2 and SSP5 increases by 18%, 13%, and 10%, respectively, indicating that crop production is mainly concentrated in the irrigated area (Tab. 3-1). In particular, the share of the irrigated area continues to rise at a steady pace in SSP1 from 2015 to 2050. By contrast, the share of irrigated area in SSP3 and SSP4 reaches the highest level in 2025 and 2015, respectively, and then decreases hereafter. This is due to large expansion of rain-fed cropland area, in particular in SAS for SSP3 and in NAM for SSP4 (Fig. B-6 in Appendix B). The relatively low initial yield of rain-fed cropland can decrease the average yield level.

Tab. 3-1. Changes in the share of irrigated area with respect to total cropland area.

Year	SSP1	SSP2	SSP3	SSP4	SSP5
1995	1.00	1.00	1.00	1.00	1.00
2005	1.03	1.01	1.01	1.03	1.01
2010	1.08	1.05	1.04	1.06	1.05
2015	1.03	1.09	1.07	1.04	0.97
2020	1.04	1.10	1.10	1.04	0.96
2025	1.04	1.10	1.13	1.01	0.96
2030	1.06	1.10	1.08	1.01	0.99
2035	1.11	1.09	1.05	0.97	1.01
2040	1.15	1.09	1.03	0.98	1.01
2045	1.17	1.11	1.03	0.99	1.03
2050	1.18	1.13	1.01	1.00	1.10

Lower yields in newly converted non-irrigated cropland in SSP3 result in lower average yields compared to SSP2, offset the effects of the higher land-use intensity in SSP3. Due to a similar reason, SSP1 has higher average yields than SSP5 despite lower land-use intensity. The findings are consistent with *Proposition B.2* derived in the method section, stating that expanding cropland into areas with lower than average yields leads to a decreasing yield index. They also explain why the order of future land productivity in the SSPs indicated by land-use intensity index is different from the order in the yield index. The combined effects of land-use intensity growth and initial yields of newly converted cropland jointly determine the changes in average yields at the regional level. Taking the regional yield index in SSP3 as an example, AFR has a larger increase in land-use intensity and average yields than LAM, because AFR has to rely on increasing technological investments for fulfilling the demand driven by very high population growth, while regions such as LAM and FSU with less increase in agricultural demand can still expand cropland area. Hence, if there is a high enough land-use intensity growth, it is possible to overcome the adverse effects of cropland expansion on average yields, resulting in an overall high average yield growth.

3.3.2 TFP growth under SSPs by 2050

Productivity growth measured by land-use intensity and yield index shows how different parts of land productivity will develop under different socioeconomic conditions. The global cumulative MPI derived in the study captures the full scope of output growth relative to growth in all the inputs including cropland area, production factor costs and amounts of water used for irrigation. The projection of TFP growth is first compared to available historical and projection data in the literature (Ludena et al., 2007). In contrast to the prediction based on the estimates of historical data, which is likely to be extrapolation of the historical productivity growth, the results in the presented study indicate that the projection has large spans when taking into account changes in socioeconomic conditions.

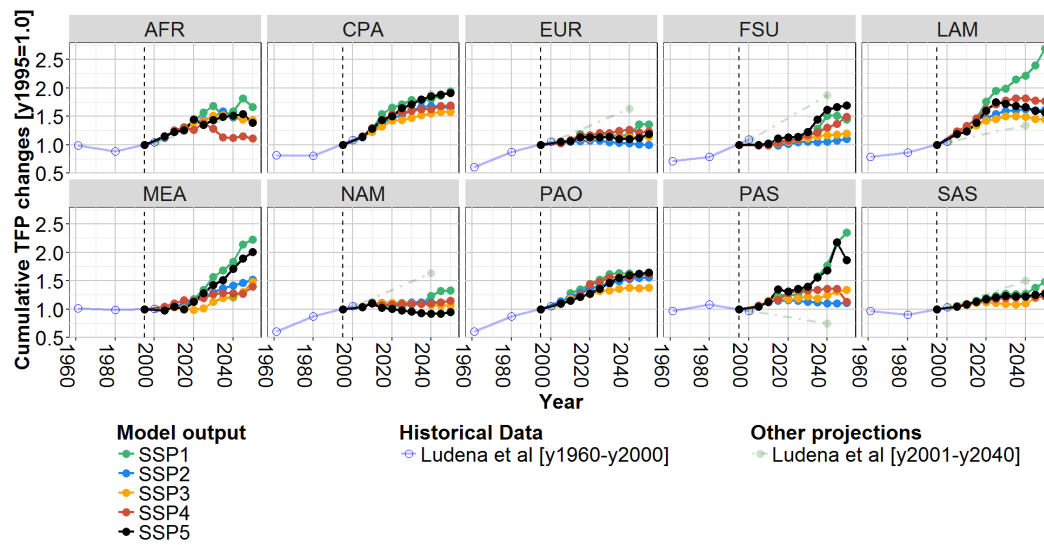


Fig. 3-2. Validation of regional cumulative TFP growth. Validation data is derived based on the annual average rate of TFP changes from periods of 1960-1980, 1981-2000, and 2000-2040 based on the study of Ludena et al. (2007).

By 2050, there is the highest growth of global TFP in SSP1 (75.9%), followed by SSP5 (42.2%), SSP4 (37.9%) and SSP2 (33.4%) (Fig. 3-3). SSP3 lies at the bottom, indicating the lowest growth in TFP, with an increase of 30.2% by 2050. Instead of relying on a limited time series of historical data to estimate TFP changes, the approach in the present study is likely to capture the structural change due to changes in socioeconomic conditions.

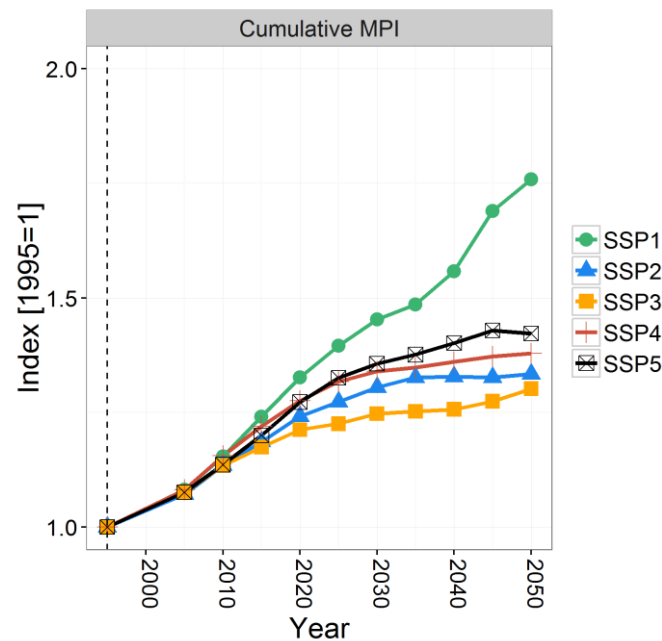


Fig. 3-3. Global cumulative TFP growth for each SSP by 2050.

TFP growth has profound implications for cropland expansion and food prices. The model results suggest that changes in food prices and cropland expansion are negatively associated with TFP growth (Fig. 3-4). The faster TFP increases, the faster food prices decrease and the slower cropland expands. SSP1 and SSP5 are projected to have pronounced TFP growth by 62.6% and 32.2%, respectively, between 2005 and 2050. The substantial TFP growth in SSP1 and SSP5 are associated with the decrease in food price (23.0% in SSP1 and 11.0% in SSP5) and minor increase in cropland area (6.2% in SSP1 and 11.2% in SSP5). In SSP2 and SSP4, there is also TFP growth but associated with an increase in food prices and slightly higher cropland expansion compared to SSP1 and SSP5. Conversely, In SSP3, food prices increase substantially, while TFP grows by 21.0% and cropland expands by 38.7% between 2005 and 2050.



Fig. 3-4. Growth rates of TFP, food prices and forest in 2050 w.r.t 2005 for the SSPs.

Global TFP growth is driven by shifts of the production frontier, i.e., technological progress rather than convergence of regions to the maximum production potential (Tab. 3-2). In particular, there is a large shift of the production frontier in SSP1 at the global level, with an annual average increase of 1.0% between 1995 and 2050. Since the global MPI is derived as a weighted average of the regional MPIs, it is worth looking at the components of TFP at the regional level. Taking SSP2 and SSP4 as examples, the higher global TFP growth in SSP4 than in SSP2 reflects that the large production regions, such as CPA, LAM, and NAM, have a higher regional TFP growth in SSP4. The order of SSPs indicated by MPI generally corresponds to the SSP narratives, in particular for SSP3. It is noticeable that regional TFP is also mainly driven by shifts of the production frontier (i.e., 32 of 40 regional catch-up scores having less than unity) except SSP5, where several regions, such as AFR, FSU, LAM, MEA, PAS, and SAS, converge to the long-term production frontier. This suggests SSP5 as a pathway with the fast convergence of productivity for developing regions. Among all regions, LAM is the only region showing

convergence (with an average annual rate of 0.1%) across all SSPs, while CPA has a unity score for convergence in all SSPs.

Tab. 3-2. Average rates of shift of technology, catch-up, and TFP change between 1995 and 2050 across the SSPs.

		AFR	CPA	EUR	FSU	LAM	MEA	NAM	PAO	PAS	SAS	GLO
SSP1	Shift of technology	1.013	1.012	1.011	1.009	1.017	1.018	1.013	1.017	1.017	1.013	1.014
	Catch-up	0.996	1.000	0.994	0.998	1.001	0.997	0.993	0.992	0.998	0.995	0.997
	TFP change	1.009	1.012	1.006	1.007	1.018	1.015	1.005	1.008	1.016	1.007	1.010
SSP2	Shift of technology	1.006	1.009	1.004	1.005	1.008	1.010	1.005	1.009	1.007	1.005	1.006
	Catch-up	1.000	1.000	0.996	0.997	1.000	0.997	0.997	0.999	0.995	0.999	0.999
	TFP change	1.006	1.009	1.000	1.002	1.009	1.008	1.003	1.008	1.002	1.004	1.005
SSP3	Shift of technology	1.007	1.008	1.003	1.005	1.006	1.008	1.004	1.007	1.008	1.004	1.006
	Catch-up	1.000	1.000	0.999	0.998	1.000	1.000	0.997	0.999	0.997	1.001	0.999
	TFP change	1.007	1.008	1.002	1.003	1.007	1.007	1.001	1.006	1.005	1.005	1.005
SSP4	Shift of technology	1.005	1.010	1.005	1.007	1.009	1.009	1.004	1.008	1.008	1.006	1.007
	Catch-up	0.997	1.000	0.999	1.000	1.001	0.997	0.998	1.001	0.994	0.998	0.999
	TFP change	1.002	1.010	1.004	1.007	1.010	1.006	1.002	1.009	1.002	1.004	1.006
SSP5	Shift of technology	1.006	1.012	1.005	1.010	1.008	1.011	1.003	1.010	1.010	1.003	1.007
	Catch-up	1.000	1.000	0.998	1.000	1.000	1.002	0.996	0.999	1.002	1.002	1.000
	TFP change	1.006	1.012	1.003	1.010	1.008	1.013	0.999	1.009	1.011	1.004	1.006

Note: Values larger than unity indicate the increase in the shift of technology/catch-up. For comparison reasons, values are shown at three digits after the decimal.

Although the average results (Tab. 3-2) show an increase in the shift of production frontier for all the regions in all SSPs, they do not identify which regions push forward the long-term production frontier. Recall that MPI measures capture the performance of productivity relative to the best practice in the sample, where best practice presents a “world frontier” (Färe et al., 1994). By looking at the component distance functions in the index of the shift of production frontier (see details in Färe et al. (1994)), the study finds that regions, such as EUR, NAM, CPA, LAM often determine the global frontier in the first time steps, CPA and LAM often determining the global frontier in the later times steps (Tab. B-3 in Appendix B). Due to the small sample size of 10 regions, it is infeasible to use techniques such as second-stage regressions (Chen et al., 2008; Headey et al., 2010) to pinpoint the underlying driving factors behind MPI. However, with a priori information from simulating land dynamics in the MAgPIE model and insights gained from analyzing PFP measures, the study can provide insights into the possible factors affecting the shift of production frontier. Taking CPA and LAM as examples, the average rate of shift of production frontier for SSPs is 0.8-1.2% and 0.6-1.7%, respectively, indicating a robust growth. One source of the shift of production frontier is due to changes in management and increases in technological investments, which is partly affected by the overall institutional environment. For instance, the empirical analysis of TFP

in the literature shows the positive impacts of institutional change on adoption of new rice varieties during the rural reform period in China (Lin, 1991). The positive effect of irrigation technologies on production is another cause of the shift of the frontier. The result is consistent with other studies that indicate that irrigation mainly affects the shift of production frontier (Fan, 1991; Jin et al., 2002; Chen et al., 2008).

3.4 Conclusion

Measuring productivity entails different ways which take into account different types of production inputs. Synthesizing the findings of productivity growth indicated by PFP and TFP measures, the results show that there is likely to be a continuous growth of global crop productivity for a broad span of different future socioeconomic conditions, but the ranking of SSPs regarding growth rates varies across productivity indicators. In particular, SSP5 has the highest land-use intensity by 2050, while SSP1 indicates the highest average yields and TFP. In a world with fast economic growth, strong governance performance and relatively slow population growth (SSP1/SSP5), food demand in 2050 can be met without aggressive cropland expansion. Productivity growth occurs through the adoption of high-yield technologies and improved irrigation. In contrast, low economic growth, weak governance performance, and very high food demand driven by fast population growth (SSP3), will require high land-use intensity together with vast cropland expansion into rain-fed areas to fulfill demands but will result in low TFP growth. Whether it is feasible to feed an increasing population under these circumstances can be doubted based on the results. A reason for concern is the low TFP growth in SSP3, especially in developing regions. Under conditions of the high population and low income growth, food insecurity in SSP3 is likely to become worse in developing regions. In all SSPs except SSP5, TFP growth is driven not only by shifts of the production frontier, based on investments in yield-augmenting technologies and management improvements affecting land-use intensity but also due to investment in irrigation technologies, which is not part of the land-use intensity measure. This confirms the necessity to invest in R&D and infrastructure to meet increasing food demand and avoid large-scale cropland expansion, especially in the face of fast population growth. SSP5 is featured as a pathway with fast convergence toward the long-term production frontier across developing regions. TFP growth has profound implications for cropland expansion and food prices. The faster TFP increases, the faster food prices decrease, and the slower cropland expands. A broad range of productivity changes under different socioeconomic conditions and according to different indicators indicates that it is equally essential to consider economic and demographic structural changes in the future and to include multiple productivity measures when projecting future productivity growth.

4 TRADING MORE FOOD IN THE CONTEXT OF HIGH-END CLIMATE CHANGE: IMPLICATIONS FOR CROPLAND DYNAMICS AND FOOD PRICES

Abstract

The study analyzes the impacts of agricultural trade liberalization on cropland dynamics and food prices in the context of high-end climate change. To this end, it employs an agro-economic dynamic optimization model, in which international trade is modeled based on a bilateral trade structure. The implementation of bilateral trade in the model enables a straightforward representation and analyses of trade policy instruments, which in reality are bilateral. Moreover, a calibration scheme is developed with the idea of tariff-quota rates to provide comparable net trade patterns, and model evaluation is extensively conducted by comparing model results concerning trade-related variables with historical data and projections. Additional scenarios regarding governance performance are included in the study to consider institutional barriers for climate adaptation regarding the difficulties of adopting agricultural technologies and advancing productivity.

The research findings suggest that liberalizing agricultural trade in terms of improving market access is likely to buffer adverse impacts of climate change on agricultural supply and limit the increase in food prices. Additional cropland expansion on the global scale could be reduced, although trade liberalization may cause cropland expansion in specific regions due to changes in trade patterns. Governance improvement is expected to reduce global cropland expansion, whereas it might lead to increases in land-use intensity as well as cropland land expansion in regions including Sub-Saharan Africa and Latin American. By considering climate projection uncertainty, the study finds that the influence of trade liberalization and governance improvement on reducing cropland expansion and limiting the increases in food prices on the global level remains robust.

Keywords: climate change, international trade, trade liberalization, governance improvement, land displacement, and food prices

4.1 Introduction

How a growing world population can be fed is one of the central questions facing our century, in particular in the presence of climate change. The observed rise in global mean temperature (GMT) exerts negative impacts on crop yields (Lobell et al., 2011), challenging sufficient global agricultural supply. Global demand for crop products is expected to double from 2005 to 2050 (Tilman et al., 2011). In addition, deployment of bioenergy, increasing material demand, and feedstock put additional pressure on agricultural production (Lotze-Campen et al., 2010).

It is widely perceived among economists that agricultural trade can serve as a key adaptation option to climate change (Reilly and Hohmann, 1993; Fischer et al., 1994; Nelson et al., 2014). As an economic adjustment, it could help alleviate the challenges caused by climate change by making use of the comparative advantages between countries (Nelson et al., 2014; Ruiter et al., 2016). Liberalizing trade is expected to increase total agricultural welfare and slow the increase in food prices (Stevanović et al., 2016), but also limit further expansion of the cropland area used for agricultural production on the global level (Schmitz et al., 2012). However, it remains unclear among existing research whether, and if so, to what extent trade liberalization will affect global land dynamics when cropland displacement effect is to be considered. Trade liberalization often reinforces spatial displacement of cropland. With increasing globalization of agricultural production, land use becomes interconnected among regions through agricultural trade (Meyfroidt et al., 2013). As a consequence, global cropland area for export production grows rapidly (Kastner et al., 2014). In particular, regions endowed with rich tropical forests, such as Latin America, tend to experience increasing cropland expansion (Schmitz et al., 2012). Studies suggest that the reallocation of natural resources embodied in agricultural goods should be considered when analyzing the trade effect (Meyfroidt et al., 2013; Kastner et al., 2014).

Current studies about effects of trade openness on land dynamics mainly focus on the historical pattern (Meyfroidt et al., 2013; Kastner et al., 2014), whereas little attention is paid to understanding future patterns, in which climate change is a factor that cannot be ignored. This study intends to fill the research gap by taking into account climate impacts and analyzing cropland displacement due to the shift of agricultural production under further trade liberalization and considers its potential impacts on food security. The challenge of analyzing the trade-offs and projecting land-use patterns is to account both socioeconomic and biophysical aspects of agricultural production within one modeling framework (Lotze-Campen et al., 2010). Linking to a global gridded dynamic vegetation model LPJmL (Müller et al., 2017) enables considering the altered biophysical conditions for crop production in the context of climate change, and the resulting reallocation of cropland through agricultural trade.

Additional to trade liberalization, increasing agricultural productivity due to technological progress is another key economic component for increase supply to meet increasing demand (Ruttan, 2002; Anderson and Martin, 2005; Josling et al., 2010; Nelson et al., 2014; Alston, 2018). Strong governance performance may facilitate increasing yields and future productivity growth by encouraging investment in agricultural technologies (see Chapter 2 and Chapter 3). The weak governance performance can become institutional barriers undermining societies' capacities for adapting to climate change (Jantarasami et al., 2010; Jones and Boyd, 2011; Moser and Ekstrom, 2010) through, for example, limiting agricultural yield increase, which is an crucial adaptation strategy in the agricultural sector (Nelson et al., 2014). Therefore, the influence of governance performance on TC is considered to be critical for affecting societies' adaption capacities and will be examined in the present study.

Hence this study assesses the impact of trade liberalization on land dynamics and food prices in the context of high-end climate change and takes into account the effects of governance performance on technological progress. The remainder of the chapter is organized as follows. Section 4.2 introduces the modeling procedure of bilateral trade structure, followed by a description of the trade data used in the analysis and calibration schemes of trade patterns. Scenarios of trade liberalization, governance performance, and climate impacts are introduced in section 4.3. Section 4.4 shows the validation results of net trade patterns. Results of trade patterns, land-use intensity, food prices, and cropland dynamics are presented in section 4.5 and discussed in Section 4.6. Section 4.7 concludes.

4.2 Methods and data

Trade policies and disputes are, in reality, often bilateral (Tongeren and Meijl, 1999). This suggests that modeling directly on the bilateral level provides additional add-on value for understanding the trade issues and their impacts on food systems and land dynamics. Different trade structures are used in the literature for analyzing trade policy (Dixon et al., 2016; Balistreri et al., 2018), and the models can be categorized with regard to the assumptions about homogenous goods and bilateral trade characteristics of the global market (Tongeren and Meijl, 1999). The Armington structure assuming imperfect substitution between domestic and imported goods (Armington, 1969), is often adopted in CGE models to capture the feature of two-way trade of a commodity (Hertel et al., 2010; Balistreri et al., 2018). The recent development of CGE models applies the Krugman structure (Krugman, 1980) or the Melitz structure (Melitz, 2003), not only enabling bilateral trade representation but also incorporating microfoundations (Dixon et al., 2016; Balistreri et al., 2018; Jafari and Britz, 2018). On the other hand, the H-O structure is commonly used in partial equilibrium models, especially when the focus is on the agricultural sector. It operates on a set of arbitrage conditions for homogenous goods (Schmitz et al., 2012; Msangi et al., 2014; Robinson et al., 2015; Balistreri et al., 2018).

Representation of trade in partial equilibrium models is often based on a pooled market (Lotze-Campen et al., 2008; Schmitz et al., 2012; Msangi et al., 2014; Robinson et al., 2015), assuming that all regions export to or import from a single global market, and not distinguishing a single separate identification of international trade by its origin and destination. In practice, the procedures applied to derive net trade patterns differ across models. The IMPACT model, for instance, relies on reduced form functions and firstly solves the equilibrium price in the world market, and then updates the quantity and price in domestic markets iteratively to reach an equilibrium (Robinson et al., 2015). AGLINK operates in a similar fashion using price transmission equations (Tongeren and Meijl, 1999). The default version of MAgPIE simulates net trade patterns based on self-sufficiency parameters, which determine the proportion of tradable goods between the pooled market and domestic markets (Lotze-Campen et al., 2008; Schmitz et al., 2012).

4.2.1 Bilateral trade representation in the model

The present study models agricultural trade as an extension of Koopmans-Hitchcock transport cost-minimization problem (Takayama, 1967), to include multiple homogenous commodities and consider trade policy instruments, which in nature are bilateral. Trade margins and tariffs drive a wedge between the price received by an exporter and the price paid by an importer and therefore can affect trade patterns (Burfisher, 2011). Let $i, ii \in I$ denote MAgPIE regions, $M = [K, L]$ refers to a set of agricultural goods, including $k \in K$ tradable commodities and $l \in L$ non-tradable goods. Let $ux_{i,ii,k}^{trade}$ denote a non-negative trade volume of commodity k between region i and ii , while $c_{i,ii,k}^{trade\ margin}$ is the trade margin between the pair of regions with units of USD/dry matter ton (DM ton), and $d_{i,ii,k}^{sdt}$ is specific duty tariffs with units of USD/DM ton. The total trade costs $f(x)$ are a function of trade volume and a vector of parameters including trade margins and tariffs, as indicated in equation (4.1). The trade costs summed over all the regions and tradable commodities are considered as part of total costs in the objective function of MAgPIE and minimized when the model is solved.

$$f(x) = \sum_{i,ii,k} (c_{i,ii,k}^{trade\ margin} + d_{i,ii,k}^{sdt}) * x_{i,ii,k}^{trade} \quad (4.1)$$

Two additional constraints as follows have to be fulfilled. Equation (4.2) refers to the export constraint, assuring that for commodity k in region i , the domestic supply must be larger than or equal to the sum of domestic demand and the total exports.

$$x_{i,k}^{production} \geq \sum_{ii} x_{i,ii,k}^{trade} \quad (4.2)$$

Equation (4.3) refers to the import constraint, indicating that for commodity k in region ii , the domestic demand must be smaller than or equal to the total amount of domestic production and the total imports.

$$x_{ii,k}^{demand} \leq \sum_i x_{i,ii,k}^{trade} \quad (4.3)$$

For non-tradable goods, regional demand must be smaller or equal to regional supply, i.e., $x_{i,l}^{demand} \leq x_{i,l}^{production}$. Following the H-O structure, the study assumes that the goods are homogenous. It is expected that regions specialize in the production and export of agricultural goods with respect to their comparative advantage. In other words, the trade structure implies that the reallocation of agricultural goods is fully based on cost competitiveness.

4.2.2 Data and parameterization

For the representation of the bilateral trade structure in MAGPIE, data of trade margins and tariffs are needed. Trade margins ($c^{trade\ margin}$) and tariffs (d_{export}^{sdt} and d_{import}^{sdt}) are calculated from the GTAP7 dataset according to the supply chain in the dataset illustrated by Hertel (1997). Trade tariffs are expressed as specific duty tariffs [USD/DM ton], for a pair of regions and for a tradable commodity, instead of the *ad valorem* term in the original GTAP dataset. For clarity, I collapse the subscripts of regions and commodities in the following equations for computing the variables.

$$c^{trade\ margin} = \frac{viws - vxwd}{vxmd} * \frac{vom}{voa} * ps \quad (4.4)$$

$$d_{export}^{sdt} = \frac{vxwd - vxmd}{vxmd} * \frac{vom}{voa} * ps \quad (4.5)$$

$$d_{import}^{sdt} = \frac{vims - viws}{vxmd} * \frac{vom}{voa} * ps \quad (4.6)$$

, where ps is the farm-gate prices of tradable goods derived from FAOSTAT (FAO, 2018); $viws$ refers to the value of imported goods at the price of cost, insurance and freight (*cif*); $vxwd$ refers to the value of exported goods at the free on board price (*fob*); $vxmd$ is the value of exported goods valued at the domestic market price; $vims$ is the value of imported goods at the domestic market price; vom is the value of goods at the domestic market price, and voa is the value of goods at the farm-gate price. Details of the derivation can be found in Appendix C.

4.2.3 Calibration of net trade volume and its validation

The implementation of the bilateral trade structure in the model enables a representation and analyses of the international market of agricultural goods, but requires a detailed database and parameterization, and is computationally intensive (Tongeren and Meijl, 1999). Since the results of trade patterns depend on the trade margins and tariffs, the model needs calibration with regard to the trade volume, either in terms of bilateral trade or net trade. The bilateral trade structure elaborated in the present study containing a large number of inequality constraints (i.e., equation (4.2) and equation (4.3) referring to export and import constraints), is featured as Mathematical Programs with Equilibrium Constraints (MPEC). This

feature makes calibrating the parameters (i.e., trade costs) numerically difficult (Jansson and Heckeley, 2009).

Methods related to this specific calibration purpose include solving a bi-level programming problem (BLPP) (Jansson and Heckeley, 2009) and using entropy estimates (Bouët et al., 2013). The BLPP approach minimizes weighted least squares errors under the constraints that the targeted parameters satisfy the Kuhn–Tucker conditions for an optimal solution of the minimization of trade costs (Jansson and Heckeley, 2009). The BARON solver features automatic reformulation of the primary functionality (Ferris et al., 2005), for solving MPEC to reach a global optimum, though at the cost of long computation time. However, as MAgPIE does not explicitly model prices as an endogenous variable, and food demand is provided exogenously, BLPP is not compatible with the current modeling framework. In MAgPIE, production information is irresponsive to the prices, that is, dual values of the constraints derived from the calibration process. Entropy calibration approaches are about using maximum entropy econometrics to rebalance input-output data (Heckeley and Wolff, 2003; Robinson et al., 2001). The only application of this approach for calibrating bilateral trade flows is conducted by Bouët et al. (2013). However, as their study only mentions how bilateral trade data is rebalanced using a cross-entropy method but does not provide any details on how the approach can adjust trade data according to trade costs, it is not possible to replicate this approach here.

Due to the incompatibility of MAgPIE with the BLPP minimization approach, an alternative calibration approach is developed in the present study to calibrate the net trade volume to the level of the year 1995 by imposing an additional cost, which penalizes the deviation from previous trade positions. The idea is consistent with the policy instrument of tariff-rate quota (TRQ), which is an additional tariff to the existing specific duty tariffs in the model. The non-negative penalty, i.e., $x_{i,t,k}^{penalty} \geq 0, \forall i, t, k$, is a linear function as follows.

$$x_{i,t,k}^{penalty} \geq a_k^{penalty_factor} * a_{i,k}^{price} * (x_{i,t,k}^{net_trade} - a_{i,t-1,k}^{net_trade}) \quad (4.7)$$

, where $a_k^{penalty_factor} \in [0,1]$ denotes a commodity-specific penalty factor, $a_{i,k}^{price}$ is a commodity-and region-specific farm-gate price, and $a_{i,t-1,k}^{net_trade}$ is quantity of net exports for region i and a commodity k in time step $t - 1$, while $x_{i,t,k}^{net_trade}$ is quantity of net exports for region i and a commodity k in the current time step t . As MAgPIE minimizes global production costs, the penalty constraint incentivizes regions to avoid changing the trade position. The calibration scheme aims to find the value of the penalty factor by solving the model iteratively until the model simulates a net trade pattern in the first time step close to the historical pattern. The calibrated penalty factor is then reused for all sequential time steps.

Extensive Model evaluation is conducted by comparing model results with various datasets including historical data and projections for trade-related variables. Firstly, model results about net trade patterns are compared with historical data from FAO. Secondly, to avoid imposing a very high penalty factor, which could render the growth rate of trade volume lower than that of production, a second criterion regarding the trade expansion rate is included in the study. This compares the trade expansion rate with the production growth rate, as international trade volumes grow faster than the production (Anderson and Martin, 2005). Thirdly, cross-validation is conducted by comparing the model outputs with projections from 11 economic models from AgMIP⁴ for the net trade pattern of coarse grain, rice and oil crops in the years 2005, 2030 and 2050, respectively.

4.3 Scenarios

In this study, I assess the effects of trade liberalization on land dynamics and food prices in the context of climate change. Climate impacts on crop yields are computed by the global dynamic vegetation model LPJmL (Müller and Robertson, 2014). To consider the upper-end climate impacts (Moss et al., 2010; Müller and Robertson, 2014; Riahi et al., 2017) on the food system and land use patterns, this study uses the representative concentration pathway with a radiative forcing of 8.5 W/m² (RCP8.5) (Moss et al., 2010). The climate projection in the RCP8.5 shows uncertainties regarding the changes in temperature and precipitation by the end of the twenty-first century (Warszawski et al., 2014; Müller and Robertson, 2014). Five different GCMs (general circulation models) from ISIMIP⁵ are used as five climate scenarios in this study to take the uncertainties of climate impacts into account. To better assess the extreme impacts of climate change and to avoid additional uncertainties (Müller et al., 2014), CO₂ fertilization is not considered in the analysis.

As the present study focuses on the economic component of the assessment, the risk accounting factors associated with investment under different governance scenarios are used to examine the different TC situations and the impacts of its interplay with trade policy and climate change on the food economy and land systems. The differences in governance performance are reflected by two scenarios of discount rates development (Fig. 4-1). Here I assume that the regional lending interest rate, as a proxy for the risk accounting factors, converges to the lower bound of 0.04. In the initial time steps, developing regions have higher discount rates than developed regions. The convergence trajectory depends on the level of

⁴ AgMIP refers to The Agricultural Model Intercomparison and Improvement Project. Models include AIM, CAPRI, ENVISAGE, EPPA, FARM, GCAM, GLOBIOM, GTEM, IMPACT, MAGNET, and MAgPIE. The models provide future projections of net trade patterns of coarse grain (excluding wheat), rice and oil crops, without considering future climate impacts.

⁵ ISIMIP refers to the Inter-Sectoral Impact Model Intercomparison Project. The GCMs used by the crop model for computing grid-level crop yields include GFDL_ESM2M, HadGEM2_ES, IPSL_CM5A_LR, MIROC_ESM_CHEM, and NorESM1_M.

GDP per capita and its development. This captures the effects of improvements in governance over time along with economic growth. In the long term, there will be only a slight difference in terms of discount rates between the two scenarios of governance performance for most regions, except AFR, FSU, and LAM.

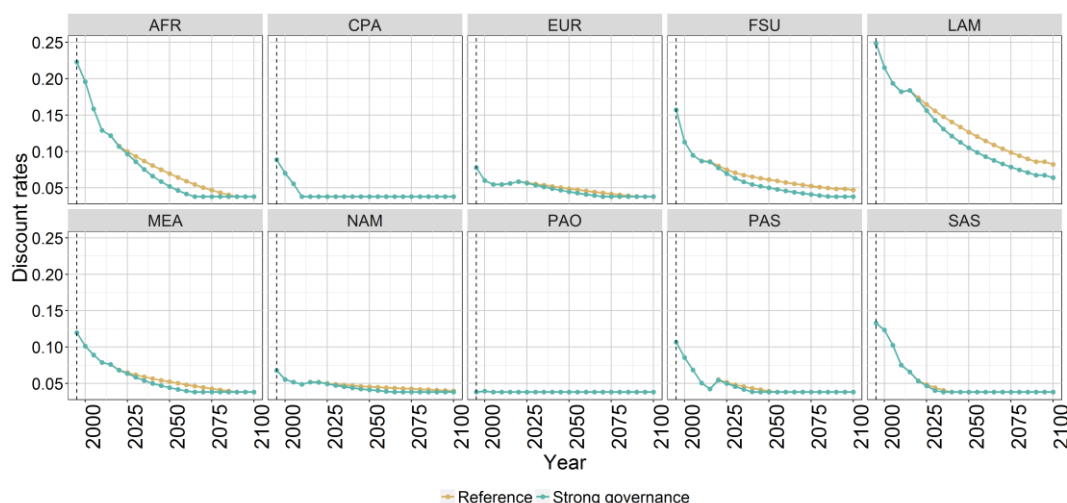


Fig. 4-1. Regional discount rates in different governance scenarios.

Two trade scenarios are developed to facilitate the analysis, including a baseline trade scenario (BAS) without reduction of trade barriers for all the regions after the year 2005, and a trade liberalization scenario (LIB) with further reduction of trade barriers. The reduction rate of trade barriers in the BAS scenario is implemented according to the WTO Uruguay Round (BAS in Tab. 4-1). The agreement entails a commitment to a tariff reduction by 36% on average for agricultural products from 1995 to 2000 for developed countries, and the time horizon of the tariff reduction was extended for four more years up to 2004 for developing countries (Anania, 2001; Sumner and Tangermann, 2002). This results in a reduction of trade barriers at an annual rate of 0.01 for developing regions in the period from 1995 to 2004, and an annual rate of 0.03 for developed regions between 1995 and 2000 (Historical period in Tab. 4-1). The LIB scenario is implemented as improving market access, in the way of reduction of tariffs and the penalty factor imposed on the deviation of trade position. Since the Doha Round negotiation continues to focus on market access (Sumner and Tangermann, 2002; Bruinsma, 2003; Anderson and Martin, 2005), the study assumes that trade barriers will be continuously reduced at an annual rate of 0.01 for all the regions from 2005 to 2100 in the trade liberalization scenario (LIB in Tab. 4-1). The principal premise of the trade liberalization scenario is the continuation of trade policies from the Uruguay Round to the Doha Round, which is debatable given the current rise of unilateralism and anti-globalization in the world. In short, the reduction rate of trade tariffs in the LIB scenario remains the same as the BAS until 2000 and then change to the scenario values from 2005.

Tab. 4-1. Annual reduction rates of trade barriers in the trade baseline (BAS) and liberalization (LIB) scenarios. Two scenarios share the same reduction rate in trade tariffs between 1995 and 2000, and differ from each other in 2005 and thereafter.

	Historical period		BAS		LIB	
	y1995	y2000	y2005	y2010-y2100	y2005	y2010-y2100
AFR	0.01	0.01	0.01	0	0.01	0.01
CPA	0.01	0.01	0.01	0	0.01	0.01
EUR	0.03	0.03	0	0	0.01	0.01
FSU	0.01	0.01	0.01	0	0.01	0.01
LAM	0.01	0.01	0.01	0	0.01	0.01
MEA	0.01	0.01	0.01	0	0.01	0.01
NAM	0.03	0.03	0	0	0.01	0.01
PAO	0.03	0.03	0	0	0.01	0.01
PAS	0.01	0.01	0.01	0	0.01	0.01
SAS	0.01	0.01	0.01	0	0.01	0.01

4.4 Results

4.4.1 Validation results of net trade patterns

The calibrated net trade pattern in 1995 is comparable to the historical pattern given by the FAO data, except for the commodity of sugarcane (Fig. 4-2). The Kendall correlation coefficient is 0.69, and the Spearman coefficient is 0.75. Both coefficients are significant at 1% level of type I error. The discrepancy for sugarcane might be attributed to the feature that MAgPIE trades primary agricultural goods only, while in reality, processed sugar is mostly traded.

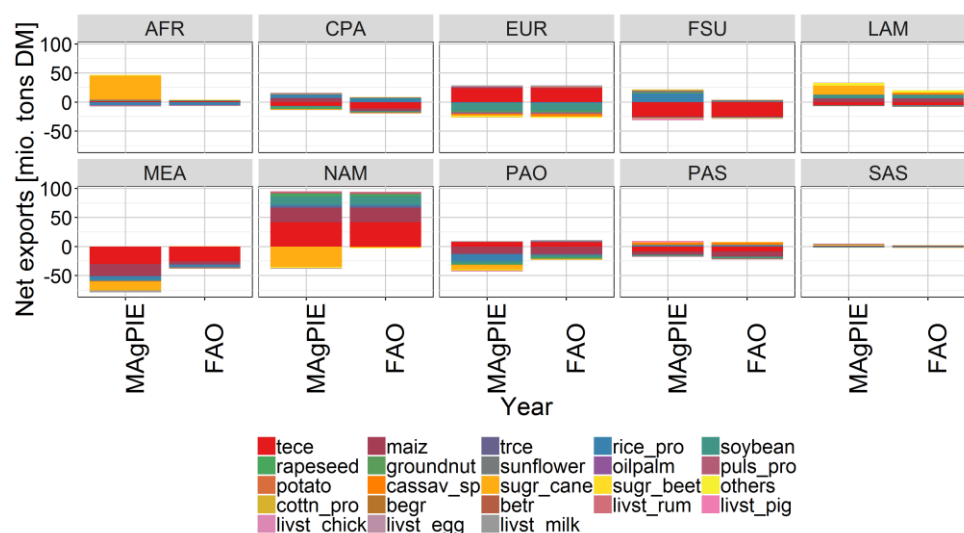


Fig. 4-2. Validation of net exports of tradable agricultural commodities in 1995 w.r.t. FAO. Tradable commodities include 18 crop commodities (temperate cereals, maize, tropical cereals, rice, soybeans, rapeseeds, groundnuts, sunflower seeds, palm oil seeds, pulses, potatoes, cassava, sugarcane, sugar beet, fruits, cotton, bioenergy crops, and bioenergy grass), and five livestock products (ruminant meat, pork, chicken, eggs, and dairy products).

The penalty factors imposed in the study results in a lower growth rate of the total export volume in 2005 and 2010, compared with historical data (Fig. 4-3). However, by comparing the growth rate of total exports with the production growth rate, the model outputs indicate that agricultural trade expands twice as fast as agricultural production, which is consistent with the empirical evidence (Bruinsma, 2003; Anderson and Martin, 2005).

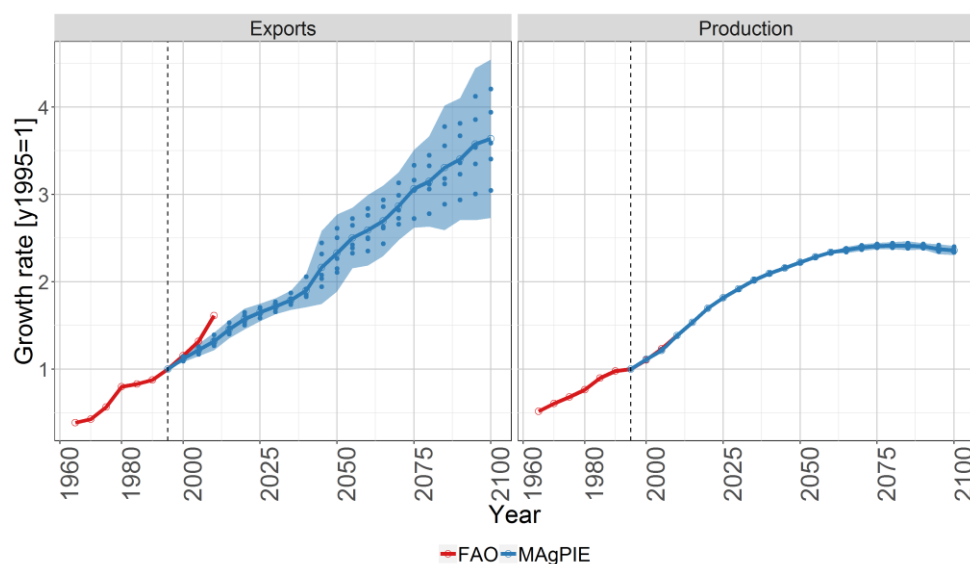


Fig. 4-3. Validation of trade expansion of tradable crop commodities. Growth rates of exports and production of crop commodities in the BAS scenario and the reference governance scenario. Actual modeled growth rates are represented by blue dots, whereas solid blue lines for all panels connect average values of calculated growth rates for each simulated time step. Shaded areas depict two times standard deviations from the sample mean.

The cross-validation results indicate that the future net trade patterns of coarse grain in the study are comparable to other model projections (Fig. 4-4). However, further improvement is still needed, as CPA exports more coarse grain than it is suggested by other models and the trade patterns regarding coarse grain in EUR and NAM are quite constant over time. The cross-validation results for oil crops and rice products can be found in Appendix C (Fig. C-1 and Fig. C-2), indicating LAM as a net importer of oil crops. This might suggest that the uniformly imposed penalty factor across regions are too high for the regions such LAM, NAM, and EUR.

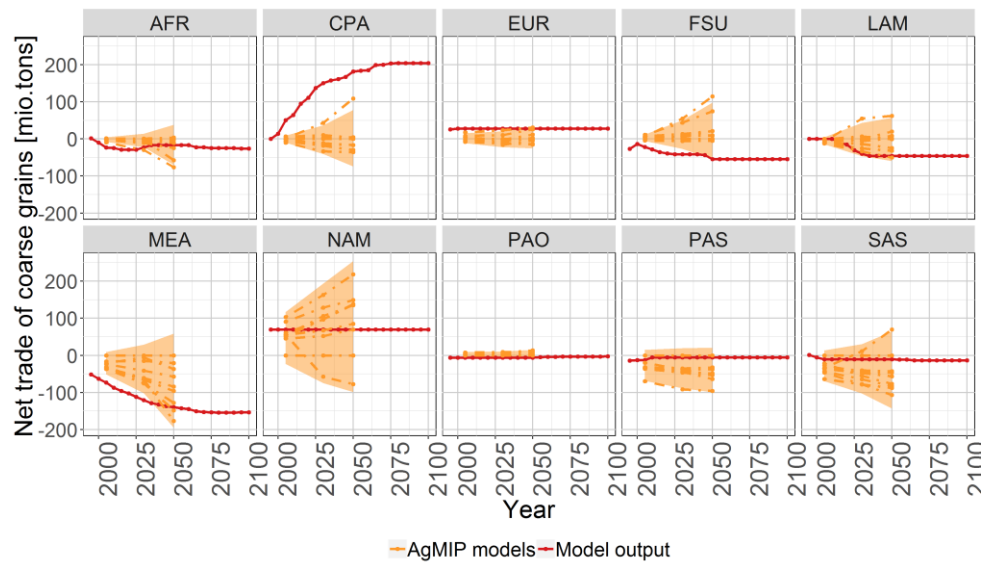


Fig. 4-4. Cross-validation of net exports of coarse grains w.r.t. AgMIP model projections in the reference governance scenario. Actual modeled growth rates are represented by red dots and lines, whereas dashed yellow dots and lines are projections from AgMIP models for each simulated time step. Shaded areas depict two times standard deviations from the sample mean of AgMIP model projections.

For analyzing agricultural trade patterns, the study mainly focuses on the results about key crop commodities including cereals (i.e., temperate cereals, tropical cereals, maize, and rice) and oil crops (i.e., soybeans, sunflower, rapeseeds, and groundnuts). The trade patterns of these commodities have been cross-validated, and they are heavily traded goods, accounting for most of the total exports of agricultural goods. The impact of livestock markets is implicitly taken into account, as regional feed demand is driven by the demand for livestock products that affects crop production.

4.4.2 Trade balances

The trade balances are calculated as net exports, namely, differences between the exports and imports of a region (Fig. 4-5). In the BAS scenario, regions including CPA, NAM, and EUR dominate exports of cereals (panel i in Fig. 4-5). CPA increases its cereal exports steadily over time and take over NAM to become the biggest exporter of cereals during the period from 2030 to 2050 as well as thereafter. In contrast, NAM and EUR have a relatively constant share concerning the export volume of cereals over time. On the imports side, MEA and AFR are the biggest importers of cereals, followed by SAS and FSU.

The situation of the exports changes slightly when the agricultural trade market is liberalized. With the trade liberalization, CPA increases the exports of cereals, for instance, by 189.1 million tons in the period from 2055 and 2075, while NAM and EUR decrease their exports. All the net importers of cereals in the BAS scenario except PAS further increase importing cereals due to the trade liberalization, especially AFR and SAS. For example, AFR increases the imports of cereals by 103.9 million tons in the LIB scenario between 2055 and 2075, compared

to the BAS scenario. Globally, trade liberalization drives the total average volume of net exports cereals to 382.9 million tons between 2030 and 2050, compared to around 291.2 million tons in the BAS scenario in the same period. Between 2080 and 2100, the average net exports of cereals increase globally to 765.3 million tons in the LIB scenario, being 1.4 times as high as in the BAS scenario.

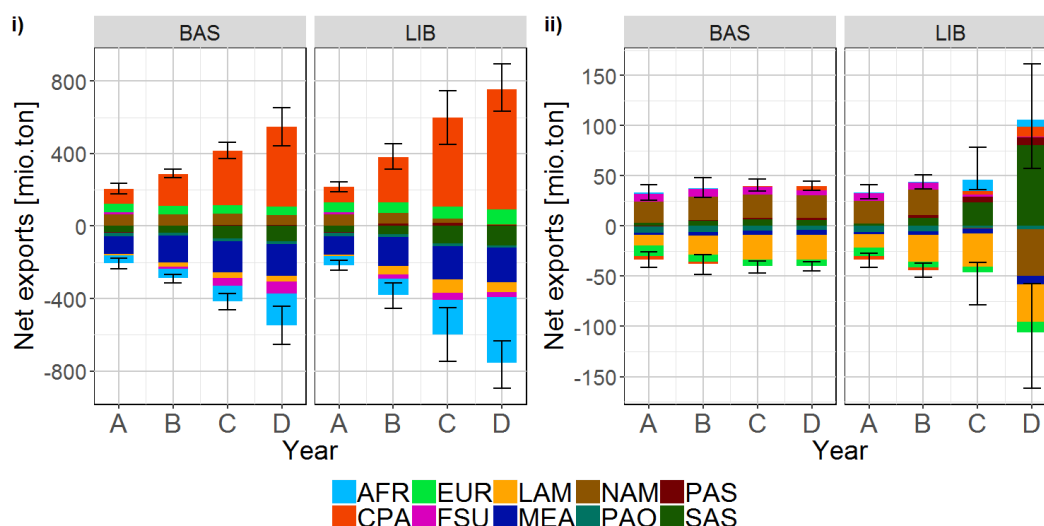


Fig. 4-5. Net exports of cereals (including rice) and oil crops for ten world geographic regions in the two trade scenarios (BAS and LIB) for four time-spans (A = 2005- 2025, B = 2030 – 2050, C = 2055 -2075, D = 2080 -2100), when the reference governance scenario is assumed. Panel i) refers to the net trade pattern of cereals, while panel ii) refers to the net trade patterns of oil crops. The height of bars indicates the averaged net exports across the five different GCMs, while the error bars refer to two times standard deviations from the sample mean of global net exports and global net imports.

Differences in the governance performance have minor effects on the global trade patterns (Fig. C-3 in Appendix C). The distribution of regions regarding exports and imports are similar between the reference and strong governance scenarios, whereas the global net exports of cereals are more significant in the former than the latter. Between 2080 and 2100, the difference in total net exports between the two governance scenarios is 65.8 million tons in the BAS scenario and 49.2 million tons in the LIB scenario, respectively. Moreover, CPA becomes less competitive in exporting cereals when there is governance improvement, although it still dominates the export market of cereals. CPA's exports of cereals decline by 69.7 million tons in the BAS scenario and even more by 102.2 million tons in the LIB scenario between 2055 and 2075, Due to the governance improvement (

Tab. 4-2). On the import aspect, the governance improvement also leads to a decline in the net imports of cereals in AFR, by 36.0 million tons in the BAS scenario and 93.3 million tons in the LIB scenario, respectively (Tab. 4-3).

Tab. 4-2. Net exports of cereals from CPA in the time-span C (2055-2075).

	Reference	Strong governance	Differences in net exports
BAS	302.8	233.1	$\Delta_{strong_governance-reference} = -69.7$
LIB	491.9	389.7	$\Delta_{strong_governance-reference} = -102.2$
Differences in net exports	$\Delta_{LIB-BAS} = 189.1$	$\Delta_{LIB-BAS} = 156.6$	

Units: million ton.

Tab. 4-3. Net imports of cereals from AFR in the time-span C (2055-2075).

	Reference	Strong governance	Differences in net imports
BAS	86.9	50.9	$\Delta_{strong_governance-reference} = -36.0$
LIB	190.8	97.5	$\Delta_{strong_governance-reference} = -93.3$
Differences in net imports	$\Delta_{LIB-BAS} = 103.9$	$\Delta_{LIB-BAS} = 46.6$	

Units: million ton.

Regions including NAM and SAS are the biggest exporters of oil crops. On the import side, LAM and EUR have the largest share of oil crop imports. PAS joins the group of exporting oil crops in the LIB scenario between 2030 and 2050. On the contrary, NAM gradually becomes a net importer at the end of the century in the LIB scenario (importing more than 46.3 million tons) albeit exporting 25.4 million tons of oil crops in the BAS scenario. Trade liberalization further intensifies exports of oil crops from SAS, while AFR, LAM, FSU, and MEA further increase their imports. Globally the net exports of oil crops in the period from 2080 to 2100 almost triple in the LIB scenario (109.6 million tons) as the BAS scenario (40.2 million tons).

The study also considers the trade balances for livestock products and sugar crops (Fig. C-4 in Appendix C). NAM dominates the livestock market with the largest share of exports, followed by CPA and FSU. Trade liberalization further increases the exports from NAM, CPA, and FSU, while SAS becomes the largest importer of livestock products. When calculating the sugar market, the model only accounts for the primary goods, i.e., sugarcane and sugar beet. Accordingly, tariffs in the model for sugar crops are based on the tariffs applied to primary goods. The underestimation of sugar tariffs based on historical data is likely to lead to unrealistic model results concerning trade balances in the sugar market. Governance improvement tends to reduce the global trade volume and reduce the competitiveness of exporters and dependence of importers, in the case of other commodities including oil crops, livestock products, and sugar crops (Fig. 4-5 and Fig. C-4).

4.4.3 Food price increases at a modest rate

Food prices in the model are represented by shadow prices, provided by solving the total production cost minimization problem, indicating the scarcity of the resources used for food production. Cereals, sugar crops, oil crops, and livestock products are among the commodities used as the basis for computing the food price index in this study. Averaged across the five GCMs, global food prices are kept at a relatively low level with a maximum increase of 4.4% in the LIB scenario, compared with the level in 2005, whereas the average food price jumps by 16.7% in the BAS scenario (panel A in Fig. 4-6). The liberalization of the agricultural trade market, achieved by increasing market access, buffers the negative impacts of climate change on food supply. As there are uncertainties regarding the future climate projections, the study takes uncertainties into account when analyzing the climate impacts on crop production and food prices. In an extreme case, the global food prices in 2085 increases by up to 37.2% compared to the level of food prices in 2005 in the BAS scenario.

Despite different regional discount rates between the two governance scenarios, the trend of developments of food prices appears similar (panel B in Fig. 4-6). As illustrated in the model, trade liberalization, instead of governance improvement, has a dominant effect on food price changes. The governance improvement leads to 5.4% decline of global food prices in the BAS scenario, and a decline by 5.7% in the LIB scenario in 2085, when the global food prices reach a peak. A reason behind is that in the reference governance scenario, fast technological progress can be expected because the discount rates decline in a fast pace along with economic growth.

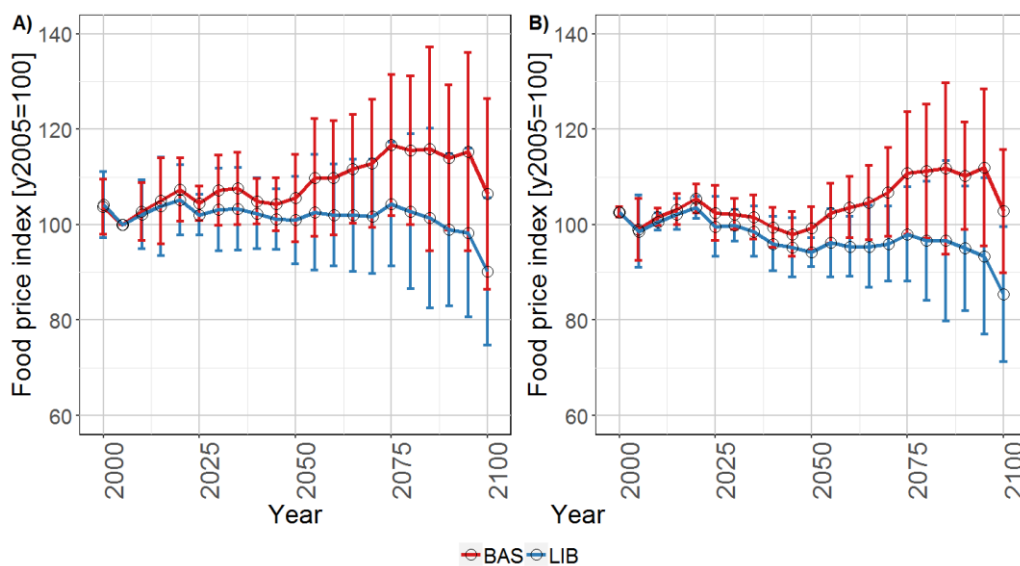


Fig. 4-6. Global food price index (normalized w.r.t. the level in 2005) in different scenarios of trade regimes for the reference governance scenario (panel A) and the strong governance scenario (panel B). The solid lines and points indicate the average food prices across five different GCMs, while the error bar refers to two times

standard deviations from the sample mean.

4.4.4 Land-use intensity growth

Regional land productivity growth responds differently to trade liberalization. The regional land-use intensity levels in CPA, FSU, PAS, AFR, and LAM (Fig. 4-7) are selected to illustrate how land productivity evolves under different trade and governance scenarios. When liberalizing agricultural trade market, regions including CPA (2.9% - 4.1%) and FSU (2.2%) experience more significant land-use intensity growth, although the increase rate varies between the reference and strong governance scenarios. By contrast, the land-use intensity declines in AFR (7% - 8.6%), LAM (9.4% - 9.7%), and PAS (3.3% - 4.8%) due to trade liberalization.

Governance improvement also has a different influence on regional land productivity growth. Improvement in the governance performance results in a decline of land-use intensity growth in CPA (1.8% - 2.9%) and PAS (3% - 5%). In contrast, governance improvement boosts the land-use intensity growth in AFR (1.2% - 2.9%), FSU (10.3%), and LAM (15.4% -15.8%). Among the five regions, land-use intensity growth in LAM is most responsive to trade liberalization and governance improvement. Appendix C (Fig. C-5 and Fig. C-6) shows the full spectrum of land-use intensity growth for all the regions and the scenarios across different GCMs.

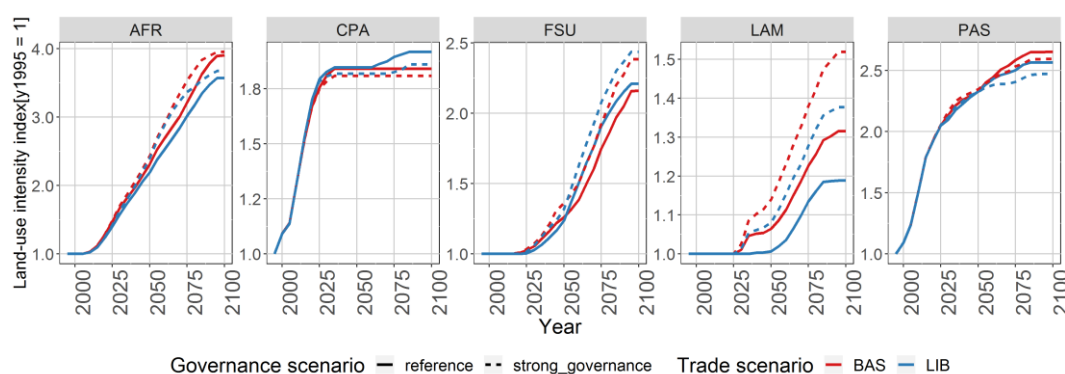


Fig. 4-7. Land-use intensity growth in selected regions (i.e., AFR, CPA, LAM, and PAS) in the different trade and governance scenarios. The values are averaged across the five GCMs.

4.4.5 Land dynamics

Global cropland area continuously increases over time until 2075 and then contracts thereafter. The model results indicate that trade liberalization is expected to avoid further expansion of cropland area on the global level, regardless of improvement in governance performance (Fig. 4-8). Averaged across GCMs, global cropland area reaches about 1849.7 million hectares by the end of the century in the BAS scenario, when the governance performance is assumed as the reference scenario. Globally, around 156.3 million hectares of cropland expansion and 37.8 million hectares of deforestation can be avoided in 2100, if

agricultural trade liberalization is achieved. On the regional level, trade liberalization shifts agricultural production to regions including CPA and PAS, leading to further cropland expansion in these two regions (panel A in Fig. C-7). For instance, CPA experiences additional cropland expansion of 23.8 million hectares in 2100 in the LIB scenario than the BAS scenario. PAS encounter additional 8.1 million hectares of cropland expansion in 2050 due to the trade liberalization.

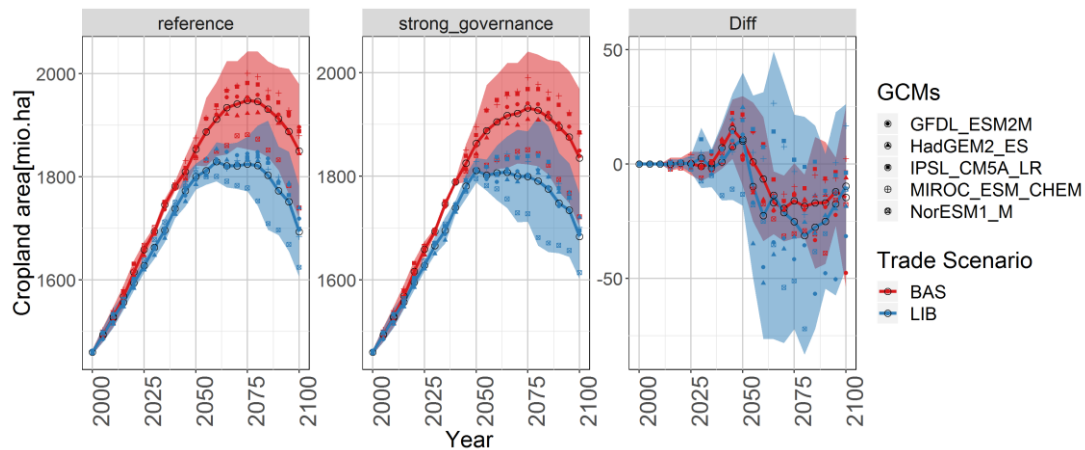


Fig. 4-8. Global cropland area in the different scenarios of trade and governance performance. The left panel indicates the cropland area in different trade scenarios, where the reference governance scenario is assumed. The middle panel indicates the results in the strong governance scenario. The right panel indicates the differences in global cropland area for each trade scenario between different governance performance scenarios (strong governance - reference). For each of the five GCMs used in the analysis, actual simulated cropland area is indicated by dots, while solid lines for each panel refer to the sample mean, averaged across the GCMs. The shaded areas depict two standard deviations from the sample mean across the GCMs.

Improving governance performance is expected to further reduce cropland in both trade scenarios on the global level (middle panel in Fig. 4-8), although the difference in global cropland expansion between the two governance scenarios is subtle (right panel in Fig. 4-8). This is partly due to the design of the governance scenarios that are implemented in the model, in which differences are only significant in developing regions including AFR, FSU, and LAM (See Fig. 4-1 in section 4.3). The impacts of the governance improvement on the regional cropland dynamics are pronounced, causing additional cropland expansion in developing regions, including FSU, PAS, AFR, and LAM (Fig. 4-9) in the BAS and LIB scenarios.

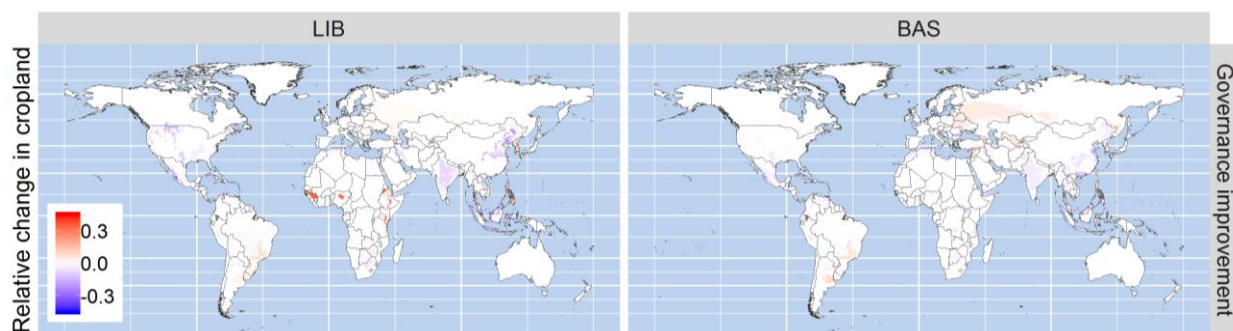


Fig. 4-9. Relative change in cropland share due to governance improvement (strong governance - reference) under different trade scenarios in 2090. The values are averaged across the five GCMs.

4.5 Discussions

4.5.1 Importance of trade liberalization for comparative advantage and land dynamics

Trade liberalization concerning reducing the tariffs is a critical economic component influencing trade patterns. Between 2005 and 2100, a reduction of trade tariffs by 61.5% is expected to drive the global net exports of cereals 1.4 times as high as in the BAS scenario in 2100. Not only the global trade volume changes but also the regional trade patterns alter with the reduction of trade tariffs. Consistent with the literature (Chaney, 2008; Kehoe and Ruhl, 2013; Baier et al., 2014; Dixon et al., 2016), the model results show that both the intensive and extensive margin of trade vary. The intensive margin of trade refers to the volume of exports from exporters, while the extensive margin is concerning the set of exporters (Chaney, 2008). Trade liberalization could further intensify the exports of cereals from CPA and exports of oil crops from SAS, while AFR, LAM, FSU, and MEA are likely to increase imports of both products further. On the extensive margin, PAS joins the group exporting cereals and oil crops in the LIB scenario.

Among the potential channels behind the trade patterns, the regional net trade patterns and land-use intensity growth react to the trade liberalization mostly in the same way. Regions such as CPA and FSU could increase the net exports of cereals and livestock products by obtaining higher land-use intensity. In contrast, other regions such as AFR, SAS, and LAM having lower land-use intensity in the LIB scenario than the BAS scenario tend to increase the net imports of cereals significantly. The interplay of cropland expansion and land-use intensity growth could affect the comparative advantage among regions and thus cropland dynamics. In a world with a continuous reduction of trade tariffs to improve agricultural market access, around 156.3 million hectares of cropland expansion and 37.8 million hectares of deforestation are likely to be avoided by 2100 on the global level. Being more dependent on the international market to feed the growing population, regions including AFR, SAS, and LAM require less cropland area for domestic agricultural production. However, trade liberalization could result in additional cropland expansion in specific regions due to changes in the trade

patterns of agricultural commodities. For example, cropland expansion increases along with land-use intensity in CPA when there is trade liberalization. In contrast, increasing agricultural outputs for exports in PAS mainly relies on cropland expansion, as the land-use intensity in PAS is between 3.3% and 4.8% lower in the LIB scenario than in the BAS scenario.

4.5.2 Importance of governance improvement for comparative advantage and land dynamics

Governance performance also affects trade patterns by influencing comparative advantage among regions. Comparative advantage may arise for regions with strong governance status quo or a fast convergence to the strong governance, which incentivizes investment in agricultural technologies and fosters technological progress. For instance, CPA and PAS have a rapid convergence to the lower bound of discount rates along with the regional economic development in the reference governance scenario and becomes the most cost-efficient in term of production as an outcome of more investment in technology, which stimulates the exports in CPA and PAS. On the other hand, regions such as LAM and AFR that experience a relative weak governance *status quo* in the reference governance scenario, are less competitive regarding exporting agricultural products.

Improvement of governance performance would encourage investments in agricultural technologies (Culas, 2007; Wang et al., 2016), especially for specific developing regions and thus increase the land productivity of these regions. Examining the result from and strong governance scenarios, I find that CPA and PAS have lower land-use intensity compared to the reference governance scenario. At first glance, it seems paradoxical that governance improvement results in a relatively lower land-use intensity in CPA and PAS. However, it is not surprising when considering that the improvement of governance could have a substantial influence on those regions (e.g., AFR and LAM) with low initial land-use intensity and relatively weak governance status quo. The interplay among regions results in the lower land-use intensity growth in CPA and PAS. As a consequence, regions such as AFR and LAM that are initially net importers in the reference governance scenario, are expected to become less dependent on the international market, when governance is improved.

Globally, the governance improvement is expected to reduce global cropland expansion by 14.5 million hectares by 2100 without considering the effect of trade liberalization. However, it is worth noting that the governance improvement might lead to increases in land-use intensity as well as cropland land expansion in specific regions including AFR, LAM, and FSU.

4.5.3 Importance of trade liberalization and governance improvement for poverty reduction

Consistent with the literature about the effects of trade liberalization on food prices (Reilly et al., 1994; Stevanović et al., 2016), this study suggests that with a continuous reduction of trade tariffs, the world is likely to have more agricultural goods traded among regions, and

global food prices are projected to be kept at a low level. To be specific, the increase rate of global food prices by 2100 could be limited to a maximum of 4.4% with trade liberalization, compared with the level in 2005. Conversely, global food prices are expected to rise by up to 37.2%, when there is no further trade liberalization after 2005. Impacts on food prices will have profound implications for the livelihoods of the poor's, who are often net consumers of agricultural commodities in developing regions. The net effects of changes in food prices on poverty reduction depend on whether poor households are net consumers or producers, and the country-level impacts are dependent on whether countries are net imports or exporters (Wodon et al., 2008; Swinnen and Squicciarini, 2012; Wang et al., 2016). The effects of food prices on consumers often outweigh that on local producers in the regions that are net importers (Wodon et al., 2008). Based on the research findings in this study, the poor in the areas such as AFR, LAM, and SAS, being highly dependent on the world market, is expected to benefit more from the trade liberalization as it can limit the increase in food prices. It is worth noting that trade liberalization could enhance the regions' resilience to climate shocks but also make them more sensitive to trade shocks (Headey, 2011; Clapp, 2015, 2017). Compared to trade liberalization, governance improvement has minor effects on food prices.

Compared to the results from other studies based on MAgPIE, the increase in food prices in this study is modest. The reasons are twofold. First, this study considers a reduction of tariffs of 34% in the BAS scenario in the period from 1995 to 2005, following the agreement on agriculture in the Uruguay Round Negotiations. This differentiates substantially from Stevanovic et al. (2016), in which they suggest that global food prices would be tripled in the period from 1995 to 2100 in an extremely stringent trade scenario with a static trade pattern. Second, Schmitz et al. (2012) show that food price will increase by around 40% in a liberalized trade scenario and by approximately 20% in an extremely liberalized trade scenarios in 2045, respectively. The comparison of the model results with Schmitz et al. (2012) indicates that the governance scenario considered in the present study could be another reason for the result of a modest increase in food prices. Wang et al. (2016) suggest that improving governance has a substantial impact on the reduction of global food prices. As shown in the present study, the relatively low food prices in the reference governance scenario without further trade liberalization after 2005 are partly due to the governance scenario featured with a fast convergence of governance performance across regions.

4.6 Conclusion

The study analyzes the impacts of agricultural trade liberalization on cropland dynamics and food prices in the context of high-end climate change. To this end, it employs an agro-economic dynamic optimization model, in which international trade is modeled based on a bilateral trade structure. The implementation of bilateral trade in the model enables a straightforward representation and analyses of trade policy. Moreover, a calibration scheme

is developed with the idea of tariff-quota rates to provide comparable net trade patterns, and model evaluation is extensively conducted by comparing model results concerning trade-related variables with historical data and projections. The finding contributes to the discussion about the up and downside of trade liberalization by extending the analysis based on bilateral trade implementation and taking into account climate uncertainties and governance performance.

The research findings show that in the scenario of high-end climate impacts on crop yields, trade liberalization plays an essential role in buffering the adverse effects of climate change on agricultural supply. Impacts of trade liberalization on food prices will have profound implications for the livelihoods of the poor's, who are often net consumers of agricultural commodities in developing regions including Sub-Saharan Africa, South Asia, and Latin America, in which food demand is expected to increase primarily due to the growth of population and income. Trade liberalization could also reduce further cropland expansion on the global scale, although cropland expansion escalates in specific regions, in which agricultural production are export-oriented. In addition to the trade liberalization, the study finds that governance improvement is expected to reduce global cropland expansion, whereas it might lead to increases in land-use intensity as well as cropland land expansion in specific regions including AFR, LAM, and FSU. Compared to trade liberalization, governance improvement has minor effects on food prices. By considering climate projection uncertainty, the study concludes that the influence of trade liberalization and governance improvement on reducing cropland expansion and limiting the increases in food prices on the global level remains robust.

There are a few caveats to the findings, which are worth further studies. By calibrating to the historical net trade pattern in the year 1995, the study replicates most of the historical patterns in regional net exports of major commodities. However, the model results for certain products (sugar) and regions (LAM) are not satisfactory, suggesting that regional drivers and market barriers are not captured completely in the current calibration scheme for the net trade patterns. Data quality issues regarding tariffs and margins are part of the general data problems. The mismatch between bilateral trade patterns and tariffs could result from the derivation of trade tariffs. The unobservable tariffs indicate that there is in reality little trade, implying high tariffs (Anania, 2001). Moreover, which data should be used as a reference for calibration raises another issue. As FAO data is expressed in quantity terms and the GTAP data is in monetary term, the recalculation of the data and disaggregation of GTAP sectors leads to inconsistency with the FAO data. For future improvement, studies could consider using emulators to introduce price responsive production in the calibration or restructuring the food demand system by incorporating the endogenous price mechanism which is essential for calibrating bilateral trade flows in the spatial price equilibrium problem.

5 SYNTHESIS AND OUTLOOK

Global agricultural models are essential for understanding challenges related to sustainable development issues in a changing world, as they consider key factors along both biophysical and socioeconomic dimensions and can provide an *ex ante* perspective for understanding their impacts on society and ecosystems. The overarching goal of the present dissertation has been to consider three key economic factors – governance performance, productivity growth, and trade liberalization – to assess their impacts on land dynamics and food systems in a changing world. I have also sought here to contribute methodologically toward improving economic representation in the MAgPIE modeling framework by incorporating the key economic factors of governance performance, different measures for productivity, and a bilateral trade structure with associated trade costs. Each of the chapters 2 through 4 have taken a very specific theoretical and methodological focus, which jointly can be considered to provide a global view for understanding issues related to sustainable development. The present section is organized as follows, following a summary of the key research findings from each chapter in section 5.1, I outline my methodological contributions in section 5.2. A reflection on key assumptions of the model used for the dissertation is articulated in section 5.3, and section 5.4 presents suggestions for future work.

5.1 Summary of key research findings

5.1.1 Governance performance affects agricultural technological progress, especially for developing regions

Research findings in **Chapter 2** suggest that governance performance has a significant impact on technological progress and land productivity growth, especially for developing regions. In 2010, Sub-Saharan Africa had the same land-use intensities under strong as well as weak governance scenarios. However, according to the model applied here, improving governance stimulates higher growth of land-use intensity by 2045. Costs for technological investments differ substantially between the two governance scenarios. In fact, such investment costs are almost four times as high in the weak governance scenario as in the strong one, due to taking into account risks associated with governance performance. Furthermore, if the costs associated with investment risks are excluded and only technological investment costs *per se* are considered, fewer investments would actually be made in the weak governance scenario, compared to the investments made under the strong governance scenario.

Looking at the risks associated with average investments in South Asia and Sub-Saharan Africa in the reference scenario, similar patterns are found. They had similar land-use intensities in 2010, but South Asia exhibited stronger governance performance than Africa in terms of things such as accountability and the rule of law. There is a similar increase in average yields due to TC expected in the two regions by 2025, but the risk-accounting costs of technological change differ greatly, being five times higher in Africa than South Asia. Developing regions,

such as Sub-Saharan Africa, tend to gain more from improvement of governance performance than developed countries, as they have relatively weak governance levels compared to developed regions. Projected growth rates for average yields attributed to land-use intensity in Sub-Saharan Africa due to improvement of governance range from 0.17 to 0.34 for the period between 2015 and 2040, which is from 0.04 to 0.14 higher than that in North America.

5.1.2 Governance improvement reduces global cropland expansion and associated deforestation

The present study has suggested that, globally, around 302.4 million hectares of cropland expansion and 195.8 million hectares of deforestation could be avoided by 2045, if governance improvement is seriously pursued. By contrast, deterioration of current governance performance could lead to an additional increase of 151.0 million hectares of cropland and 95.8 million hectares of deforestation by 2045 on the global level. Cropland expansion generally occurs in regions which have large endowments of the forest, particularly tropical forest. These regions, including Sub-Saharan Africa, Latin America, and Southeast Asia, are often characterized by unstable political and economic conditions. Strong governance is likely to lead to lower cropland expansion globally, mainly due to moderate cropland expansion rates and high land-use intensity growth that may be achieved in developing regions (i.e., Latin America, Former Soviet Union countries, South Asia, Sub-Saharan Africa, and Southeast Asia). For instance, in Latin America and Southeast Asia, the land-use intensity in 2045 under strong governance is projected to be 36.3% and 47.5% higher, respectively, than under weak governance. Weak governance and fragmented governance result in large areas of additional cropland required for agricultural uses, which often comes at the expense of losing forest.

5.1.3 Governance improvement is essential for local livelihoods and poverty reduction in developing regions

Chapter 2 has also looked into the implications of governance performance for local livelihoods and poverty reduction based on the research findings regarding food prices and trade patterns of major food commodities under different governance scenarios. The analysis presented here indicates that Sub-Saharan Africa and South Asia tend to be net importers under the weak governance scenario and that global food prices will be higher than under the strong governance scenario. In particular, food prices in Sub-Saharan Africa would be more than ten times higher under the weak governance scenario than the strong and four times higher in South Asia. Considering that countries in Africa and Southeast Asia are mainly net importers of temperate cereals, it is reasonable to expect that the higher food prices are projected to result from weak governance will undermine global efforts toward reducing poverty, ultimately resulting in higher poverty, although some local producers are likely to benefit. Moreover, because these two regions generally exhibit low income levels combined

with high shares of income being spent on food, increased food prices caused by weak governance are very likely to not only raise poverty rates but mostly hurt those who are already poor. Weak governance performance could also cause higher poverty in the urban area in Latin America since the urban residents are often net consumers of food and the region has a large proportion of the poor living in urban areas.

5.1.4 Implications of socioeconomic conditions for productivity changes

Building upon the research presented in **Chapter 2**, I have gone a step further by including additional productivity estimates – that is, an average yield index and Malmquist productivity index (MPI) – to assess future potential of global productivity growth under different socioeconomic conditions. The research findings from the model presented in **Chapter 3** suggest that global productivity growth is likely to continue. However, the magnitude of the growth rate under different socioeconomic conditions will vary, and different productivity indicators suggest different growth rates.

Differences between the socioeconomic conditions modelled have led to a spread in the productivity. In particular, SSP5 has the highest land-use intensity growth by 2050, whereas SSP1 exhibits the highest growth in average yields and TFP. In a world with rapid economic growth, strong governance performance and relatively slow population growth (SSP1/SSP5), the model projects that food demand in 2050 can be met without aggressive cropland expansion through productivity growth, occurring through adoption of high-yield technologies and improved irrigation. In contrast, low economic growth, weak governance performance and very high food demand, driven by rapid population growth (SSP3), will require high land-use intensity together with aggressive cropland expansion into rain-fed areas to fulfill demand but will result in low TFP growth. Whether it is feasible to feed an increasing population under these circumstances can be doubted, based on the results. A reason for concern is the low TFP growth in SSP3, especially in developing regions. Under conditions of high population and low income growth, food insecurity in SSP3 is likely to become worse in developing regions. In all SSPs except SSP5, TFP growth is driven mainly by shifts of the production frontier. This confirms the necessity to invest in research and development and infrastructure to meet increasing food demand and avoid large-scale cropland expansion, especially in the face of rapid population growth. Among the results, SSP5 is featured as a pathway with speedy convergence toward shifting the long-term production frontier across developing regions.

TFP growth has profound implications for cropland expansion and food prices. The faster TFP increases, the faster food prices decrease, and the slower cropland expands. The broad range of productivity changes suggest that it is equally essential to consider economic and demographic structural changes in the future and to include multiple productivity measures when projecting future productivity growth.

5.1.5 Trade liberalization affects comparative advantage and land dynamics

Chapter 4 suggest that the reduction of trade tariffs is projected to stimulate global trade volume and further intensify the exports of cereals from China and exports of oil crops from South Asia. Regions including Sub-Saharan Africa and Latin America are likely to increase imports of both products further. On the extensive margin, Southeast Asia might join the group exporting cereals and oil crops due to trade liberalization. Among the potential channels behind the trade patterns, the regional net trade patterns and land-use intensity growth could respond to the trade liberalization mostly in the same way. The interplay of cropland expansion and land-use intensity growth could affect the comparative advantage among regions and cropland dynamics.

Trade liberalization has a significant effect on curbing global cropland expansion. In a world with a continuous reduction of trade tariffs to improve agricultural market access, around 156.3 million hectares of cropland expansion and 37.8 million hectares of deforestation are likely to be avoided globally. Trade liberalization could, however, result in additional cropland expansion in specific regions, such as China and Southeast Asia, due to changes in the trade patterns of agricultural commodities. China is projected to encounter additional cropland expansion of 23.8 million hectares in 2100, and Southeast Asia would face additional 8.1 million hectares of cropland expansion in 2050 due to the trade liberalization. Land-use intensity increases along with cropland expansion in China, while increasing agricultural output for export by Southeast Asia will mainly rely on cropland expansion. The model results indicate that South Asia will experience comparatively less cropland expansion as well as lower increases in land-use intensity if trade is liberalized.

5.1.6 Trade liberalization increases trade expansion and limits the increase of food prices

Chapter 4 suggests that trade liberalization in terms of tariff reduction stimulate global trade volume and plays an essential role in buffering the adverse effects of climate change on agricultural supply. Between 2005 and 2100, a reduction of trade tariffs by 61.5% is expected to drive the global net exports of cereals 1.4 times as high as in the BAS scenario in 2100. Global food prices can be kept at a low level, with a maximum increase of 4.4% compared to the level in 2005 due to trade liberalization. Conversely, global food prices are expected to rise by up to 37.2%, when there is no further trade liberalization after 2005. Impacts on food price changes could have profound implications for poverty reduction in the world and locals' livelihoods. Since the effects of food prices on consumers often outweigh that on local producers in the regions that are net importers (Wodon et al., 2008), regions such as AFR, LAM, and SAS, being highly dependent on the world market, are expected to benefit from the trade liberalization with limited increase in food prices. It is worth noting that trade liberalization could enhance the regions' resilience to climate shocks but also make them more sensitive to trade shocks.

5.2 Methodological contributions

In this dissertation, I have contributed to the MAgPIE modeling framework for addressing global sustainable development issues in the following three ways. Firstly, the analysis conducted here takes into account governance performance, which has been largely missing in global analyses so far, and its impacts have not been examined on a global basis, although the importance of policy and institutions has been extensively discussed in the theoretical literature and studied at the local level. The work presented here has used lending interest rates as discount rates to reflect risk-accounting factors associated with different governance scenarios. Regionally specified discount rates, rather than an identical global discount rate, provides a better picture of the governance situation of a region, which can have a significant impact on cropland expansion and agricultural technological investment. This approach is further improved in Chapter 4, based on panel data analysis to project governance performance in the future, which depends on the level of GDP per capita. This approach enables identification and analysis of effects due to improvement of governance performance over time, along with economic growth.

Secondly, I have introduced a method to estimate TFP and PFP indicators from MAgPIE model projections to assess future potential of global crop productivity growth under different socioeconomic conditions. In addition to applying a land-use intensity index, average-yield index and MPI are derived to estimate PFP and TFP growth, based on model outputs. The relationship between land-use intensity and average yields are formally analyzed. Moreover, instead of relying on estimates of historical time series data of productivity, the model-results based approach takes changes of future socioeconomic conditions into account, when estimating long-term production frontier. This is meant to enhance the understanding of productivity growth in the crop sector, additional to the development of endogenous land-use intensity growth within the modeling framework. Regional TFP change is estimated for each world region as an output Malmquist productivity index (MPI), which is based on estimates of the Shephard output distance function using the data envelopment analysis (DEA) method to construct a piece-wise linear production frontier for each year in the sample (Färe et al., 1994; Nin et al., 2003; Coelli and Rao, 2005). This approach allows differentiation between the shift of production frontier and catch-up to the frontier. The study sought to estimate global TFP changes consistently by adapting the theoretically justified method developed by Färe and Zelenyuk (2003) and Zelenyuk (2006) to construct a weighted average index that is based on the distance functions estimated from regional data with appropriate weighting.

Thirdly, being in line with neoclassical trade theory, the study has simulated agricultural trade based on a bilateral trade structure to incorporate trade tariffs directly. The study has modeled agricultural trade as an extension of the Koopmans-Hitchcock transport cost-minimization problem for multiple homogenous commodities, in order to consider trade

policy instruments in a bilateral form. A model operating directly on trade tariffs and trade margins that affect cost competitiveness among regions, enables straightforward analysis regarding effects of trade policies in terms of market access. The study further develops a calibration scheme, calibrating net trade volumes to the level of the year of 1995 by imposing an additional costs which penalize the deviation of previous trade position. A set of statistical measures and validation methods are derived to verify whether the trade calibration scheme delivers comparable model outputs. Validation of model results regarding trade patterns are extensively conducted by comparing the net trade patterns to the historical pattern in 1995, and cross-validated with the future projections from other economic models, and trade growth rate is used as an additional criterion for validating model performance.

5.3 Methodological caveats

The caveats related to the individual studies that comprise this dissertation have been discussed in each respective chapter. In this section, however, I would like to add reflections on trade calibration issues and implementation of price inelastic demand in MAGPIE, as they are critical for the results obtained and could be further developed to improve model features in the future.

5.3.1 Implications of trade calibration scheme for model results

By calibrating to the model results to historical net trade patterns in the year 1995, the study replicates most of the historical patterns in regional net exports of major commodities. However, the model results for specific products (e.g., sugar) and regions (such as LAM) are not likely to be representative because regional drivers and market barriers are not captured entirely in the current calibration scheme for the net trade patterns. The discrepancy for sugarcane might be attributed to the feature that MAGPIE trades primary agricultural goods only, while in reality processed sugar is mostly traded. Trade data, which is notoriously complex, is sometimes inconsistent, and often of bad quality. The mismatch between bilateral trade patterns and tariffs could result from the derivation of trade tariffs. The unobservable tariffs indicate that there is in reality little trade implying high tariffs (Anania, 2001). Moreover, which data should be used as a reference for calibration imposes another issue for evaluating the model results. As FAO data is expressed in quantity terms and the GTAP data is in the monetary term, the recalculation of the data and disaggregation of GTAP sectors leads to inconsistency between FAO data and GTAP data.

Implementation of bilateral trade structure is not generally difficult as such, whereas calibrating bilateral trade flows is a challenge. The net trade calibration method developed in the ideation does not guarantee an accurate representation of bilateral trade flows. For future improvement, studies could consider using emulators to introduce price responsive production in the calibration or restructuring the food demand system by incorporating the endogenous price mechanism which is essential for calibrating bilateral trade flows in the

spatial price equilibrium problem. In the long term, alternative structures of trade representation based on modern trade theory could be considered, such as Krugman or Melitz trade representation in a partial equilibrium setting. The development of model features depends largely on the research questions and also has to consider the computational complexities.

5.3.2 Inelastic food demand

As MAGPIE has been developed with a strong focus on the production aspect of the agricultural sector, featuring with detailed representation of biophysical processes, food demand representation in MAGPIE assumes an ex ante exogenous demand trajectory based on long-term income and population growth. It is debatable to what extent long-term food demand is elastic to food prices. However, ignoring the price responsiveness of demand in global land-use models could understate changes in production and fail to capture changes in prices (Baldos and Hertel, 2013). Although income has a strong effect on demand compared to price effects, empirical evidence shows that food demand is elastic in low-income countries (Hertel, 2011). Results in Chapter 3 about extremely increase in global food prices and cropland area in the SSP3 scenario is caused by the inelastic demand feature in the model. With the price responsive demand, it is expected that the actual demand will decrease and so will the cropland area required for production. Results in Chapter 2 indicate that improving governance could decrease deforestation and deforestation on the global scale, which is partly due to the cost minimization model assuming exogenous demand. Jevon's paradox is likely to arise when global food demand is responsive to price, and average yields in some regions are relatively low (Hertel et al., 2014).

Taking into account price effects is also likely to improve the representation of international trade (Tongeren and Meijl, 1999). Furthermore, by incorporating the endogenous price feature, the bilateral trade representation becomes a spatial price equilibrium model (Samuelson, 1952; Takayama and Judge, 1964), for which economic theories and tools, including BLPP, have been developed and provides a basis for calibrating the bilateral trade flows as stated in Chapter 4.

5.4 Suggestions for future research

The dissertation has sought to contribute to our understanding of governance impacts, by proposing methods for quantifying its impacts on land dynamics, food security and trade patterns. Further, I have investigated different measures of productivity growth and the implications of total factor productivity growth under different scenarios, bringing them together to better understand productivity growth in the agricultural sector. Moreover, with the development of trade representation based on a bilateral trade structure and associated trade costs, the method facilitates the analysis about impacts of trade liberalization on cropland dynamics and food prices in the context of high-end climate impacts, on the direct

basis of reduction of trade tariffs. Along with these findings at hand, taking into consideration of the key economic factors, there are three areas, which has mentioned but has not been deeply explored within the analysis presented here, worthwhile for further research.

5.4.1 Impacts of governance performance on forest protection and transport infrastructure

One research finding that has been repeatedly mentioned throughout this dissertation is that governance improvement reduces cropland expansion and lowers food prices on the global level, by stimulating investment in agricultural technology to increase land productivity. Another important aspect of improving governance is enhancing policy effects related to forest protection, as these policy instruments also depend on the general state of governance. In other words, governance performance affects transaction costs, such as monitoring costs associated with, for example, forest protection. Building upon the studies conducted for and presented through this dissertation and including transaction costs into MAgPIE, the co-benefits of governance improvement can be analyzed not only from the perspective of increasing land productivity but also in terms of dedicated forest-protection policy on the global and regional levels.

Another important issue that could be further analyzed is assessing the impacts of governance performance on the development of transport infrastructure which, in turn, affects land dynamics, especially for deforestation in tropical regions. The relationship between transport infrastructure development and land degradation has been empirically tested (Deng et al., 2011), and so is other aspect on economic growth and welfare improvement (Chaney 2008, Donaldson 2018). The trade-offs and synergies can be further extended by considering impacts of governance on the investment in transport infrastructure. Based on the recently updated data of travel time (Weiss et al., 2018), development of transport infrastructure can be endogenously modeled by considering impacts of governance performance on investment risks associated with infrastructure development.

5.4.2 Assessing impacts of key factors on total factor productivity growth

This dissertation has sought to show that a non-parametric approach for analyzing total productivity growth can enable differentiation of shift of production frontier and catch-up effects. Future research can use the growth accounting approach to compute TFP growth as the Solow residuals and to compare the results of TFP growth from the present study. This approach requires all price information of all input factors, which can be derived from shadow prices from resource constraints in MAgPIE. Particular attention should be paid to deriving land rent, which requires considering all the constraints involving the variable of cropland area in MAgPIE. Moreover, a scenario including only one variable instead of a set of variables could improve the understanding of the influence of key factors on TFP growth, for instance, only varying discount rates and assessing impacts of governance performance on TFP growth.

5.4.3 Assessing impacts of regional agricultural market integration

This dissertation has strived to show how trade is another decisive factor for affecting land dynamics and food prices. With the feature of the bilateral trade structure developed, it may prove worthwhile taking a further step to look at the impacts of regional market integration. Such studies have been conducted from a general economic perspective to analyze impacts on the whole economy (Burfisher et al., 2001). With the partial equilibrium modeling framework at hand, the impacts of regional agricultural market integration on land dynamics and food prices can be studied in detail. This has become a quite relevant question, as indicated by recent examples, such as the renewed version of NAFTA, United States-Mexico-Canada Agreement (USMCA), and ongoing negotiations about the Trans-Pacific Partnership (TPP), which have been sparking discussion among academicians, policy makers, and lobby groups (see the AAEA session at AASA 2019 and the talk given by van der Mensbrugghe at Farmers' Foundation in 2018) (van der Mensbrugghe, 2018; Schmitz and Seale Jr, 2019; Shaik, 2019). It is often not the case that global trade liberalization goes hand-in-hand with regional market integration (Schmitz and Seale Jr, 2019; Shaik, 2019). Together with the very recent development of flexible regional aggregation in MAgPIE (Dietrich et al., 2018), answering these kinds of questions become feasible and will contribute to our understanding about the possible future socioeconomic pathways featuring inequality and fragments between the developed and developing worlds.

Overall, this dissertation has sought, from an economics perspective, to improve the representation of key economic components for understanding their impacts on land dynamics and food prices, an important but remain understudied issue. With the development of the MAgPIE model, the study has contributed to our knowledge on assessing socio-economic and environmental impacts of economic factors. Along with the suggested topics for future research mentioned above, this dissertation will function as a basis for the study of sustainable development issues with an emphasis on the economic components of the agricultural production and their implications for the environment.

Appendices

Appendix A: Supplementary material to Chapter 2 (Taking account of governance: implications for land-use dynamics, food prices, and trade patterns)

A.1 Additional figures and tables

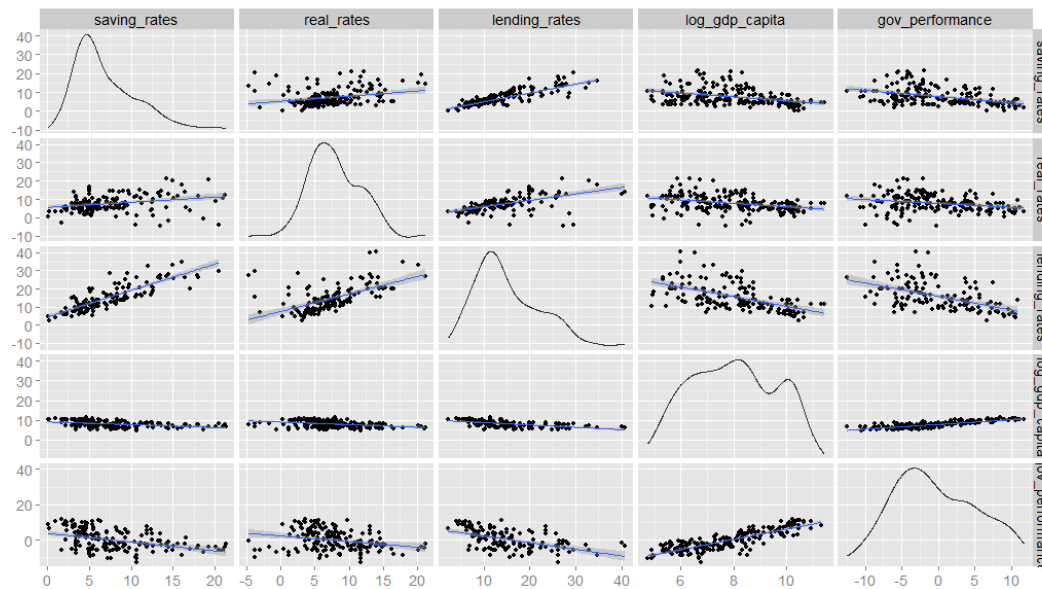


Fig. A-1. Correlation between different discount rates, governance and GDP per capita.

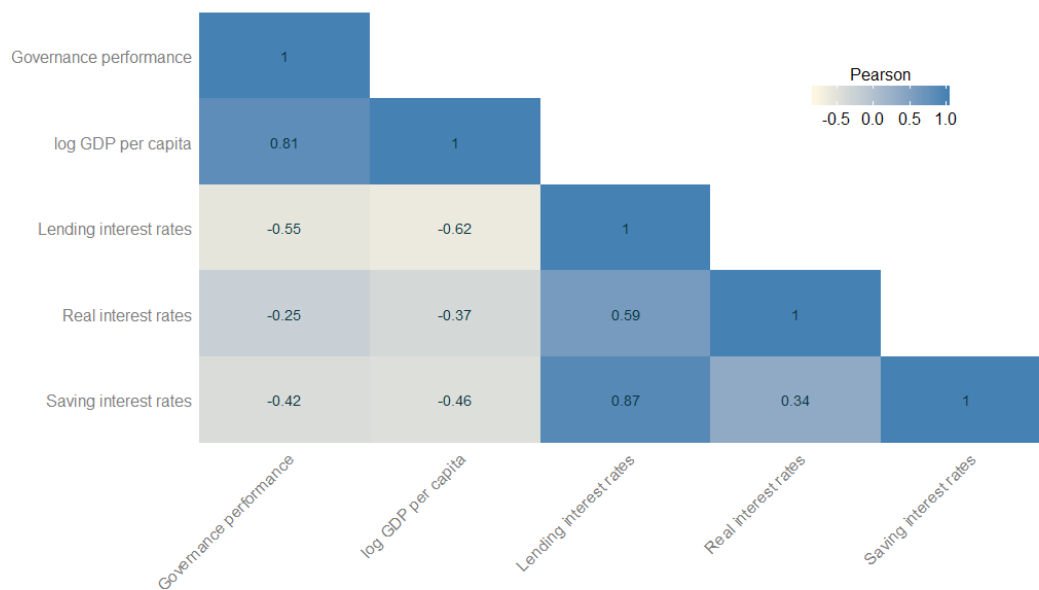


Fig. A-2. Correlation coefficients between different sets of discount rates, GDP, and governance.

Note: all the coefficients are statistically significant at 99.99% level.

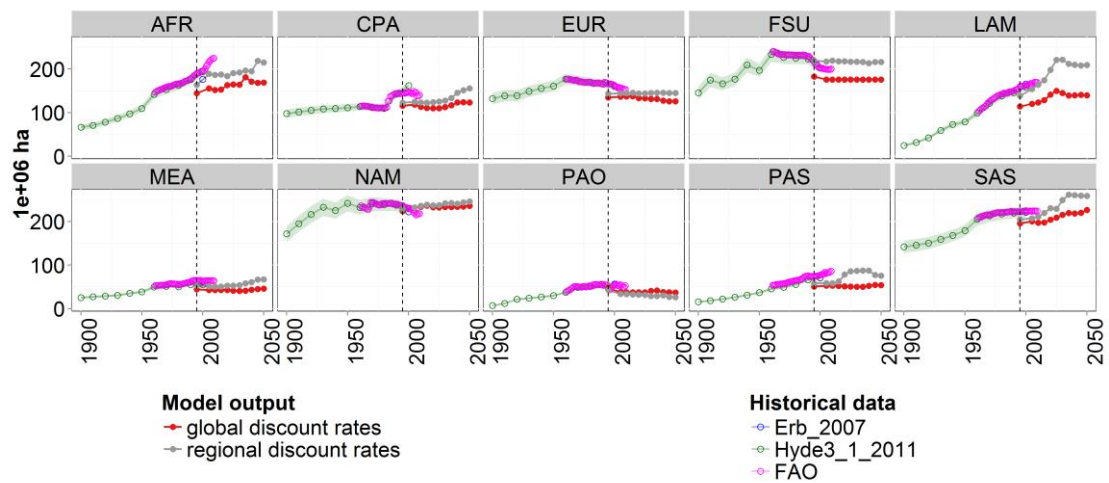


Fig.A-3. Cropland area validation.

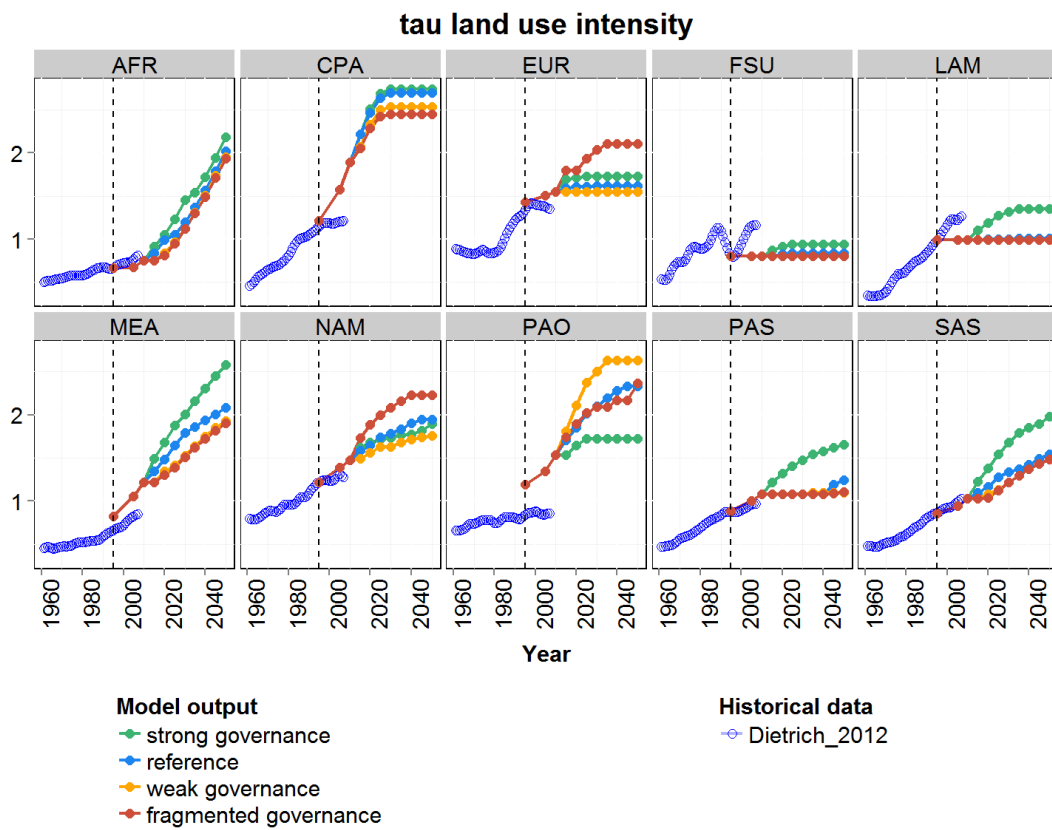


Fig. A-4. Regional agricultural productivity index. Change of agricultural productivity at the regional level over time.

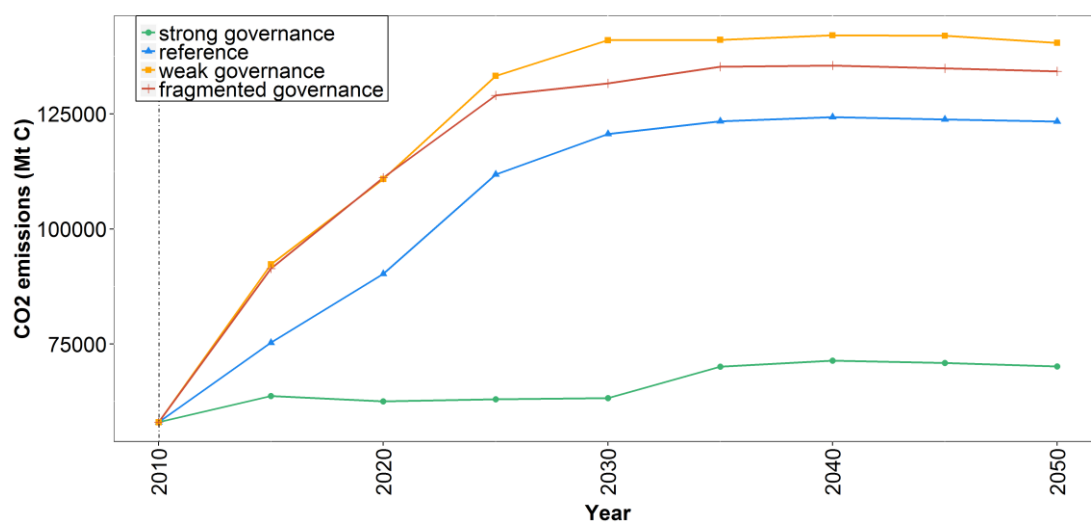


Fig. A-5. Global carbon emissions over time w.r.t. 2010.

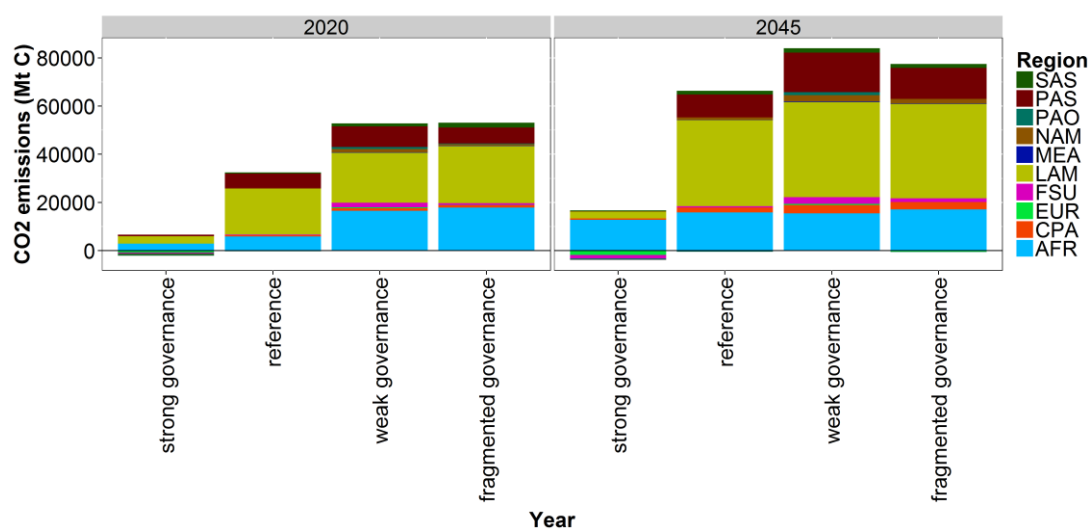


Fig. A-6. Carbon emissions at the regional level in 2020 and 2045 w.r.t. 2010.

Tab. A-1. Regional food price index. Average of regional food price index in different governance scenarios.

	Strong governance	Reference	Weak governance	Fragmented governance
AFR	43.6	148.0	557.8	539.8
CPA	58.9	88.4	142.8	123.1
EUR	72.1	103.4	143.3	85.9
FSU	49.8	90.6	129.4	115.6
LAM	61.9	134.6	176.8	152.8
MEA	67.6	113.8	193.3	172.4
NAM	71.9	107.9	147.6	83.8
PAO	83.1	105.1	134.8	93.1
PAS	67.8	99.0	129.7	113.3
SAS	62.1	108.7	224.4	214.4

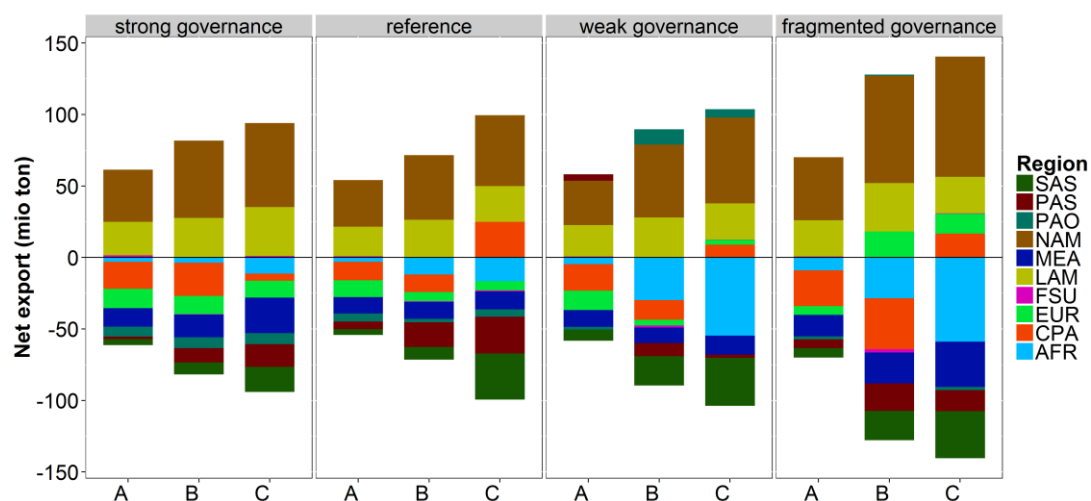


Fig. A-7. Net exports of oil crops over time (A = 2010-2020; B = 2025-2035; C = 2040-2050).

Appendix B: Supplementary material to Chapter 3 (Beyond land-use intensity: assessing future potential of global crop productivity growth under different socioeconomic pathways)

B.1 Static analysis of average yields

The yield index is calculated as follows.

$$x_{i,t}^{yield} = \frac{\sum_k x_{i,t,k}^{production}}{\sum_k x_{i,t,k}^{area}} \quad (1)$$

$$= \frac{\sum_k \sum_{j_i} \sum_w p_{j,k,w,t}^{cliamte} p_{j,k,w}^{refyield} f_{i,t}^{growth}(\cdot) x_{j,t,k,w}^{area}}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}}$$

In accordance with SSP narratives, this study assumes there are no climate impacts on yields, namely $p_{j,k,w,t}^{cliamte} = 1$. Hence,

$$x_{i,t}^{yield} = \frac{\overbrace{\sum_k \sum_{j_i} \sum_w p_{j,k,w}^{refyield} f_{i,t}^{growth}(\cdot) x_{j,t,k,w}^{area}}^{=x_{i,t,k}^{production}}}{\underbrace{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}}_{=x_{i,t,k}^{area}}} \quad (2)$$

$$= \frac{f_{i,t}^{growth}(\cdot) \sum_k \sum_{j_i} \sum_w p_{j,k,w}^{refyield} x_{j,t,k,w}^{area}}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}}$$

$$= f_{i,t}^{growth}(\cdot) \sum_k \sum_{j_i} \sum_w \omega_{j,t,k,w} p_{j,k,w}^{refyield}$$

, where $\omega_{j,t,k,w} = \frac{x_{j,t,k,w}^{area}}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}}$

$$\frac{\partial x_{i,t}^{yield}}{\partial f_{i,t}^{growth}(\cdot)} = \sum_k \sum_{j_i} \sum_w \omega_{j,t,k,w} p_{j,k,w}^{refyield} \geq 0, \quad \forall i, t \quad (3)$$

$$\frac{\partial x_{i,t}^{yield}}{\partial p_{j,k,w}^{refyield}} = f_{i,t}^{growth}(\cdot) \omega_{j,t,k,w} \geq 0, \quad \forall j, k, w \quad (4)$$

Proposition B.1 If land-use intensity increases or the initial yields increase, average yields will increase.

$$\begin{aligned}
\frac{\partial x_{i,t}^{yield}}{\partial x_{j,t,\tilde{k},\tilde{w}}^{area}} &= \frac{f_{i,t}^{growth}(\cdot) p_{j,\tilde{k},\tilde{w}}^{refyield}}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}} - \frac{f_{i,t}^{growth}(\cdot) \sum_k \sum_{j_i} \sum_w p_{j,k,w}^{refyield} x_{j,t,k,w}^{area}}{(\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area})^2} \\
&= \frac{f_{i,t}^{growth}(\cdot)}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}} (p_{j,\tilde{k},\tilde{w}}^{refyield} - \frac{\sum_k \sum_{j_i} \sum_w p_{j,k,w}^{refyield} x_{j,t,k,w}^{area}}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}}) \\
&= \frac{f_{i,t}^{growth}(\cdot)}{\sum_k \sum_{j_i} \sum_w x_{j,t,k,w}^{area}} \Delta \geq 0
\end{aligned} \tag{5}$$

$$\begin{aligned}
&\forall j, t, k, w, \text{ where } \Gamma \subset J, \Gamma^c \cap J = \tilde{J} \\
&\Delta := p_{j,\tilde{k},\tilde{w}}^{refyield} - \sum_k \sum_{j_i} \sum_w \omega_{j,t,k,w} p_{j,k,w}^{refyield}
\end{aligned}$$

$$\Delta \geq 0 \Leftrightarrow p_{j,\tilde{k},\tilde{w}}^{refyield} \geq \sum_k \sum_{j_i} \sum_w \omega_{j,t,k,w} p_{j,k,w}^{refyield} \tag{6}$$

Proposition B.2 If cropland expands, average yields will not necessarily increase, which depends on the initial yield of the newly converted cropland. Only if the initial yield is large or equal to the average yield of the existing cropland, the average yield will increase.

B.2 Derivation of global MPI

The aggregation scheme in the study is adopted according to the method derived by Färe and Zelenyuk (2003) and Zelenyuk (2006) based on production duality. Global MPI is derived using revenue efficiency and revenue shares of a region, which is based on revenue function, a dual representation of production technology. Recalling the definition of technical efficiency, it is easy to see that revenue efficiency equals the reciprocal of Shephard distance function, under regularity conditions of production technology and assumptions of the additive structure of aggregation and convexity of the aggregated output sets.

Dual analogy of a regional MPI is

$$RM^i(\cdot) \equiv RM^i(p_s, p_t, y_s^i, y_t^i, x_s^i, x_t^i) = \left[\left(\frac{RE_s^i(x_t^i, y_t^i, p_t)}{RE_s^i(x_s^i, y_s^i, p_s)} \times \frac{RE_t^i(x_t^i, y_t^i, p_t)}{RE_t^i(x_s^i, y_s^i, p_s)} \right)^{-1} \right]^{\frac{1}{2}} \tag{7}$$

Then the global analog of equation (7) is

$$\overline{RM}(p_s, p_t, \bar{Y}_s, \bar{Y}_t, X_s, X_t) = \left[\left(\frac{\overline{RE}_s(X_t, \bar{Y}_t, p_t)}{\overline{RE}_s(X_s, \bar{Y}_s, p_s)} \times \frac{\overline{RE}_t(X_t, \bar{Y}_t, p_t)}{\overline{RE}_t(X_s, \bar{Y}_s, p_s)} \right)^{-1} \right]^{\frac{1}{2}} \tag{8}$$

,where \overline{RM} is global revenue function with

Assuming the output price vector is the same for all regions. The measuring of productivity changes between periods s and t is,

$$\begin{aligned}
\overline{RE}_\psi(X_\phi, \bar{Y}_\phi, p_\phi) &= \sum_{i=1}^I RE_\psi^i(x_\phi^i, y_\phi^i, p_\phi) \times S_\phi^i, \quad \phi, \psi = s, t \\
&\text{, where } S_\phi^i \equiv \frac{p_\phi y_\phi^i}{p_\phi \bar{Y}_\phi}, i = 1, \dots, I; \phi = s, t
\end{aligned} \tag{9}$$

Plugging equation (9) into equation (7), then group analogy of dual version of MPI can be written as,

$$\overline{RM}(\cdot) = \left[\frac{\sum_{i=1}^I RE_s^i(x_t^i, y_t^i, p_t) \cdot S_t^i}{\sum_{i=1}^I RE_s^i(x_s^i, y_s^i, p_s) \cdot S_s^i} \times \frac{\sum_{i=1}^I RE_t^i(x_t^i, y_t^i, p_t) \cdot S_t^i}{\sum_{i=1}^I RE_t^i(x_s^i, y_s^i, p_s) \cdot S_s^i} - 1 \right]^{\frac{1}{2}} \quad (10)$$

Recover the global MPI based on production duality using equation (7) as

$$\overline{M}(\cdot) = \left[\left(\frac{\sum_{i=1}^I [D_s^i(x_t^i, y_t^i)]^{-1} \cdot S_t^i}{\sum_{i=1}^I [D_s^i(x_s^i, y_s^i)]^{-1} \cdot S_s^i} \times \frac{\sum_{i=1}^I [D_t^i(x_t^i, y_t^i)]^{-1} \cdot S_t^i}{\sum_{i=1}^I [D_t^i(x_s^i, y_s^i)]^{-1} \cdot S_s^i} \right)^{\frac{1}{2}} \right] \quad (11)$$

This study adapts the approach derived by Färe and Zelenyuk (2003) and Zelenyuk (2006) to use output shares as weights, which are equivalent to revenue shares if there is only a single output (Zelenyuk, 2006).

B.3 Additional figures and tables

Tab. B-1. MAgPIE parameters of the five SSPs.

Indicators	MAgPIE parameters	SSP1	SSP2	SSP3	SSP4	SSP5
Population	Population	low	medium	high	medium	low
Economy	GDP	medium	medium	low	low	high
Environment	Forest/ecosystem protection rate	high	medium	low	medium	medium
Technology	Technological change costs	medium	medium	medium	medium	medium
	Livestock intensification	fast	fast	slow	slow	fast
	Nutrient efficiency	high	medium	low	high	medium
Globalization	Free trade pool	globalized	regionalized	fragmented	globalized	globalized
Other	Demand for livestock products	low	medium	high	medium	high
	Food demand incl. Food waste	low	medium	high	medium	high
Institutional development	Risk-accounting factors associated with investments	low	medium	high	divergent	low

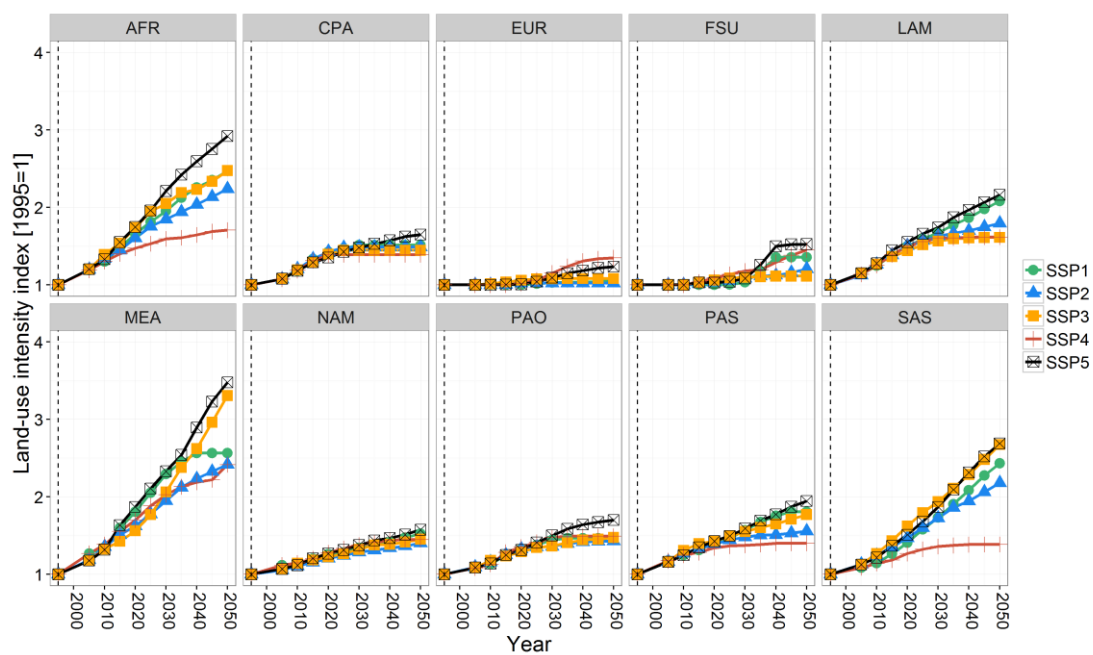


Fig. B-1.Regional productivity indices: land-use intensity growth for SSPs in 1995 - 2050.

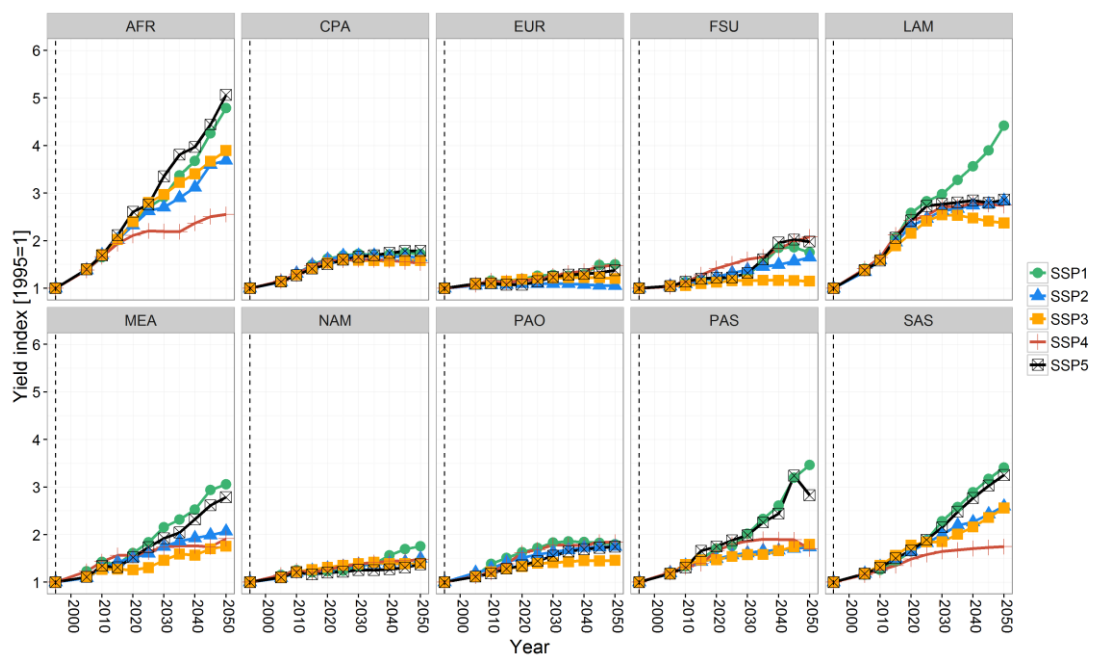


Fig. B-2. Regional productivity indices: yield index across SSPs in 1995 - 2050.

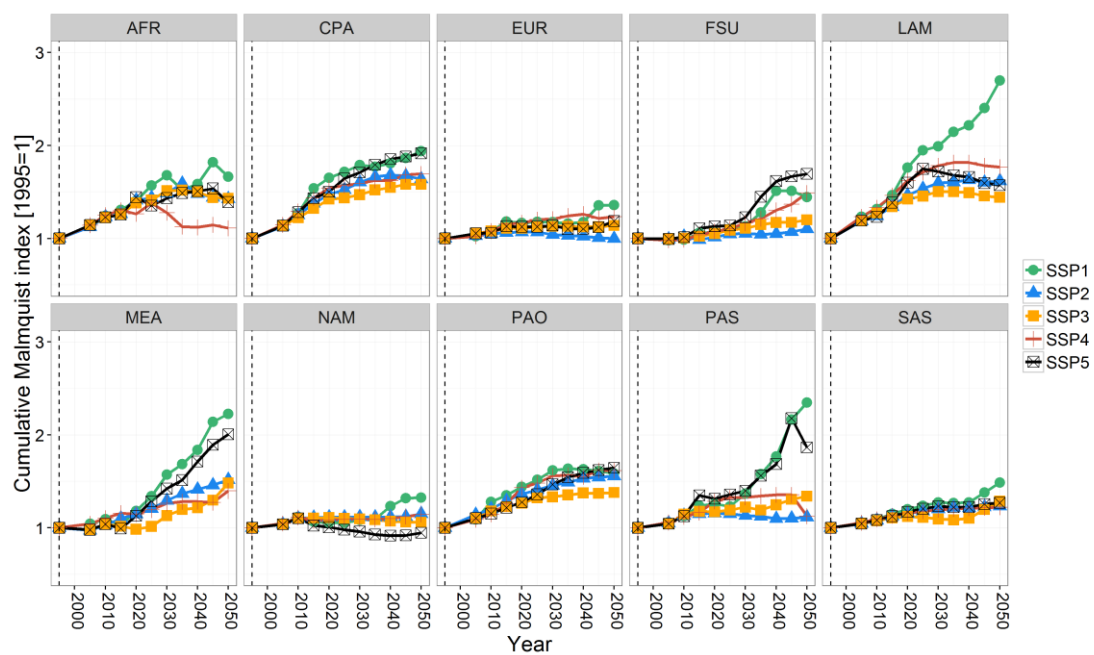


Fig. B-3. Regional productivity indices: cumulative TFP growth for each SSP in 1995 - 2050.

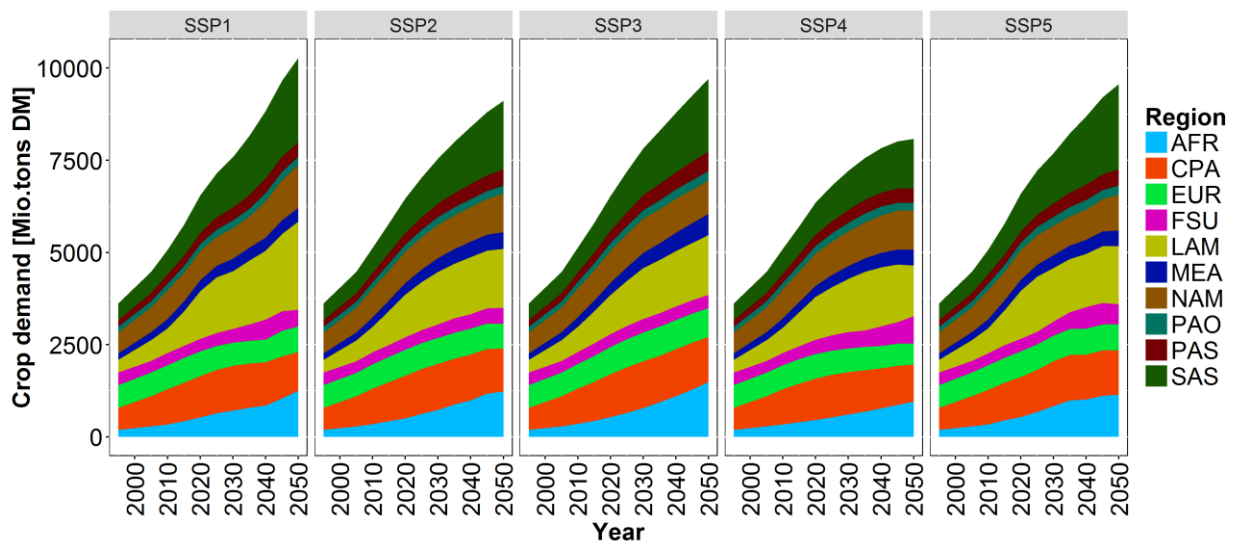


Fig. B-4. Projections of crop demand between 1995 and 2050 under SSPs.

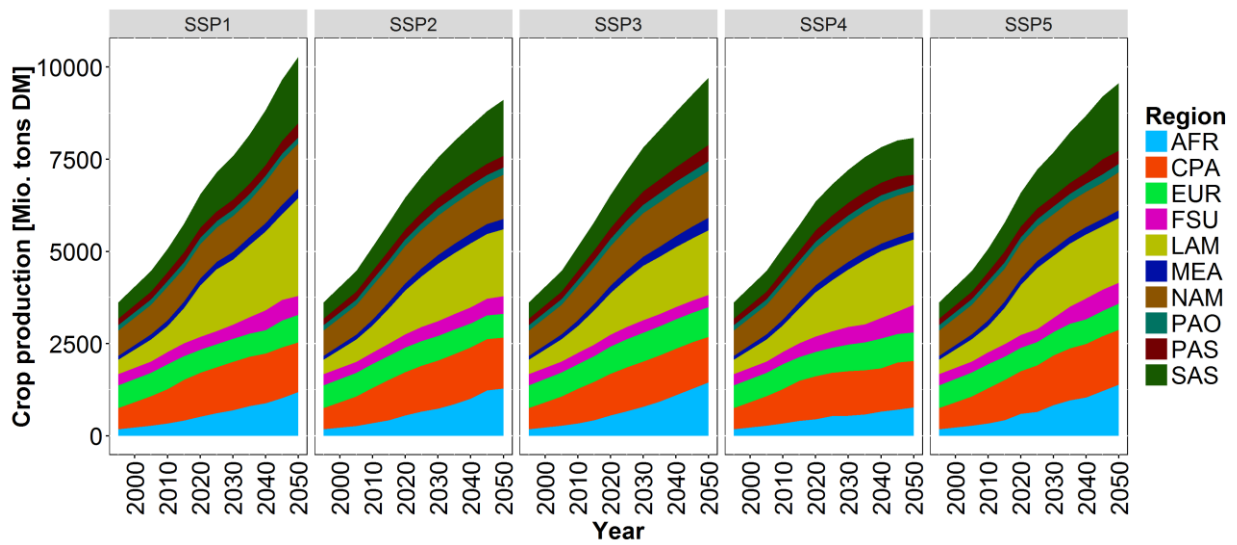


Fig. B-5. Projections of crop production between 1995 and 2050 under SSPs.

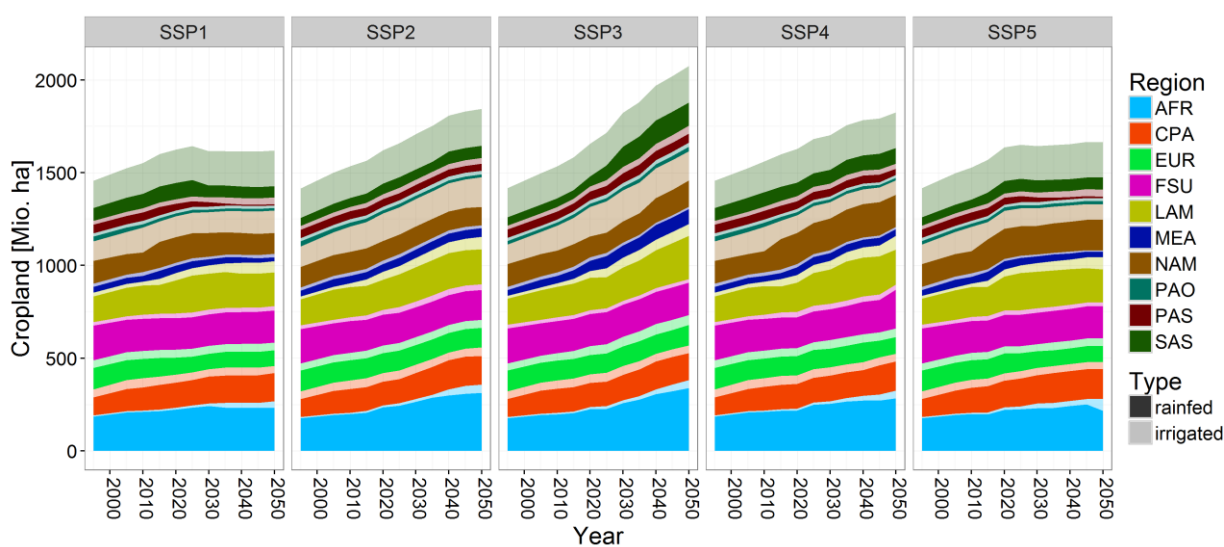


Fig. B-6. Cropland expansion in global economic regions in 1995-2050 across SSPs.

Tab. B-2. Water used for irrigation in 1995-2050[km³/yr].

	SSP1	SSP2	SSP3	SSP4	SSP5
Average	4531.82	5011.82	4983.64	4598.73	4368.55
1995	3947.00	3954.00	3937.00	3947.00	3937.00
2005	4258.00	4280.00	4219.00	4258.00	4219.00
2010	4492.00	4496.00	4429.00	4470.00	4412.00
2015	4333.00	4778.00	4683.00	4528.00	4198.00
2020	4518.00	4971.00	4929.00	4652.00	4348.00
2025	4503.00	5147.00	5218.00	4644.00	4347.00
2030	4540.00	5261.00	5337.00	4717.00	4390.00
2035	4699.00	5325.00	5342.00	4735.00	4432.00
2040	4805.00	5483.00	5435.00	4811.00	4445.00
2045	4837.00	5683.00	5608.00	4835.00	4508.00
2050	4918.00	5752.00	5683.00	4989.00	4818.00

Tab. B-3. Regions shifting the frontier.

Year	SSP1	SSP2	SSP3	SSP4	SSP5
y1995-y2005	AFR,CPA,EUR,LAM,NAM	AFR,CPA,EUR,LAM,NAM	AFR,CPA,EUR,LAM,NAM	AFR,CPA,EUR,LAM,NAM	AFR,CPA,EUR,LAM,NAM
y2005-y2010	AFR,CPA,EUR,LAM,NAM	AFR,CPA,EUR,LAM,NAM	AFR,CPA,EUR,LAM,NAM,PAO	AFR,CPA,EUR,LAM,NAM	AFR,CPA,EUR,LAM,NAM
y2010-y2015	AFR,CPA,EUR,LAM	AFR,CPA,EUR,LAM	AFR,CPA,EUR,LAM	AFR,CPA,EUR,LAM	AFR,CPA,LAM
y2015-y2020	AFR,CPA,LAM	AFR,CPA,LAM	AFR,CPA,LAM	CPA,EUR,LAM	AFR,CPA,LAM
y2020-y2025	AFR,CPA,LAM	AFR,CPA,LAM	AFR,CPA,LAM	AFR,CPA,EUR,LAM	CPA,LAM
y2025-y2030	AFR,CPA,LAM	AFR,CPA,LAM	AFR,CPA,LAM	CPA,EUR,LAM	CPA
y2030-y2035	LAM	AFR,CPA,LAM	AFR,CPA	CPA,EUR,LAM	AFR,CPA
y2035-y2040	CPA,FSU,LAM	CPA,LAM	CPA	EUR,FSU,LAM	AFR,CPA,FSU
y2040-y2045	CPA,LAM	CPA,LAM	CPA	CPA,FSU	AFR,CPA,FSU,PAS
y2045-y2050	CPA,LAM	LAM	CPA	CPA,FSU	CPA,FSU

Appendix C: Supplementary material to Chapter 4 (Trading more food in the context of high-end climate change: implications for land displacement and food prices)

C.1 Estimation of bilateral trade costs

Trade margins ($c^{trade\ margin}$) and tariffs (d_{export}^{sdt} and d_{import}^{sdt}) are estimated by following the supply chain illustrated by Hertel (1997) in the GTAP dataset. The estimation question boils down to find the relationship between the estimated variables and the farm-gate price. ps corresponds to the farm-gate price with a unit of USD/ton DM. $viws$ refers to the value of imported goods at the world market price; $vxwd$ refers to the value of exported goods at the free on board price (fob); $vxmd$ is the value of exported goods valued at domestic market price; $viws$ is the value of imported goods at the price of cost, insurance and freight (cif); $vims$ is the value of imported goods at the domestic price; vom is the value of goods at the domestic market price, and voa is the value of goods at the farm-gate price. \widehat{ps} is derived from FAOSTAT (FAO, 2018).

Tab. C-1. Description of all known variables in the GATP7 dataset used for the calculation.

Variable	$vxwd$	$vxmd$	$viws$	$vims$	$vtwr$	vom	voa
Meaning	Value of exported goods measured at fob	Value of exported goods valued measured at the domestic price	Value of imported goods measured at cif	Value of imported goods measured at the domestic price	Value of trade margins	Value of goods measured at the domestic market price	Value of goods measured at the farm-gate price

Note: all the variables are with a unit of USD.

Tab. C-2. Description of unknown variables during the intermediate step of the calculation. The variables are canceled out on the later stage of the calculation.

Variable	pm	qxs	qo	$xtax$	$mtax$
Meaning	Domestic market price	Quantities of exported goods	Quantities of produced goods		
Unit	USD/ton	Mio.ton	Mio.ton	Mio.ton	Mio.ton

Tab. C-3. Description of unknown variables during the intermediate step of the calculation. The variables will be received by the variable in Tab.C-1.

Variable	$v\acute{o}m$	$q\grave{x}s$	\acute{c}	$vxwd$	$xtax$	$m\acute{t}ax$
Meaning	Ratio of vom to voa	Ratio of exported quantity to domestic production quantity	Ratio of trade margins to value of exported goods measured at pw	Ratio of value of exported goods measured at pw to value of exported goods valued measured at <i>fob</i>	Ratio of export tariff value to value of exported goods valued measured at the domestic market price	Ratio of import tariff value to value of exported goods valued measured at the domestic market price

Note: all the variables are with a unit of one.

C.1.1 Estimation of trade margins

Equation are reformulated as a given definition of revenue in terms of a produce of price and quantity.

$$vxwd = vxmd + xtax \equiv pm * qxs \quad (1)$$

$$vom \equiv pm * qo \quad (2)$$

$$vom = voa + ptax$$

$$voa \equiv ps * qo \quad (3)$$

$$v\acute{o}m := \frac{vom}{voa} \quad (3')$$

$$\Rightarrow vom = v\acute{o}m * voa \quad (3'')$$

Combine (1) and (2)

$$q\grave{x}s := \frac{qxs}{qo} = \frac{vxmd}{vom} \quad (4)$$

$$\Rightarrow vxmd = q\grave{x}s * vom \quad (4')$$

$$\acute{c} := \frac{vtwr}{vxwd} = \frac{viws - vxwd}{vxwd} \quad (5)$$

$$\Rightarrow vtwr = \acute{c} * vxwd \quad (5')$$

$$vx\grave{w}d := \frac{vxwd}{vxmd} \quad (6)$$

Rearrange (6) using (4') , (3'') and (3)

$$\begin{aligned}
vxwd &= vxwd * vxmd = vxwd * qxs * vom * voa \\
&= vxwd * vxmd = vxwd * qxs * vom * ps * qo \quad (6'')
\end{aligned}$$

Plug (6'') in (5')

$$\begin{aligned}
vtwr &= \dot{c} * vxwd * qxs * vom * ps * qo \quad (5'') \\
vtwr &\equiv c^{trade\ margin} * qxs \\
vtwr &= c^{trade\ margin} * qxs * qo \quad (7)
\end{aligned}$$

Let (5'') equal to (7)

$$\begin{aligned}
\hat{c}^{trade\ margin} &= (\dot{c} * vxwd * vom) * \widehat{ps} \\
&:= A * \widehat{ps} \quad (7')
\end{aligned}$$

$$with\ A = \frac{viws - vxwd}{vxwd} * \frac{vxwd}{vxmd} * \frac{vom}{voa} = \frac{viws - vxwd}{vxmd} * \frac{vom}{voa} .$$

C.1.2 Estimation of export tariffs

Export tariffs are derived as specific duty tariffs as follows.

$$\begin{aligned}
xtax &= vxwd - vxmd \\
xtax &:= \frac{xtax}{vxmd} = \frac{vxwd - vxmd}{vxmd} \quad (8) \\
xtax &= xt\dot{a}x * vxmd \quad (8')
\end{aligned}$$

With (4'), (3''), and (3)

$$\begin{aligned}
xtax &= xt\dot{a}x * qxs * vom \\
&= xt\dot{a}x * qxs * vom * voa \\
&= xt\dot{a}x * qxs * vom * ps * qo \quad (8'') \\
xtax &\equiv d_{export}^{sdt} * qxs \quad (9)
\end{aligned}$$

Plug (4) in (9)

$$xtax = d_{export}^{sdt} * qxs * qo \quad (9')$$

Let (8'') equal to (9')

$$\begin{aligned}
\widehat{d_{export}^{sdt}} &= xtax * vom * \widehat{ps} \\
&= \frac{vxwd - vxmd}{vxmd} * \frac{vom}{voa} * \widehat{ps}
\end{aligned} \tag{10}$$

C.1.3 Estimation of import tariffs

Import tariffs are derived as specific duty tariffs as follows.

$$\begin{aligned}
mtax &= vims - viws \\
mtax &:= \frac{mtax}{vxmd} = \frac{vims - viws}{vxmd}
\end{aligned} \tag{11}$$

$$mtax = mtax * vxmd \tag{11'}$$

With (4'), (3''), and (3)

$$= mtax * qxs * vom * ps * qo \tag{11'}$$

$$mtax \equiv d_{import}^{sdt} * qxs \tag{12}$$

Plug (4) in (12)

$$mtax = d_{import}^{sdt} * qxs * qo \tag{12'}$$

Let (11') equal to (12')

$$\begin{aligned}
\widehat{d_{import}^{sdt}} &= mtax * vom * \widehat{ps} \\
&= \frac{vims - viws}{vxmd} * \frac{vom}{voa} * \widehat{ps}
\end{aligned} \tag{13}$$

C.2 Estimate of the effect of GDP per capita on risk accounting factors

A linear panel model with a log-log functional form and two-way fixed effects specification is assumed to estimate the effects of GDP per capita on risk-accounting factors associated with governance performance. To account for potential endogeneity between governance performance and GDP per capita, the time-lagged variable of GDP per capita is used as IV. By controlling country and time effects, within estimates indicate that GDP per capita has a negative and significant effect on the risks associated with governance performance, suggesting that if GDP per capita increases by 1%, the risk account factor will decrease by 0.43%.

$$\ln Y_{i,t} = \alpha + \beta \ln GDP_capita_{i,t} + \varepsilon_{i,t}, \quad i = 1, \dots, N, t = 1, \dots, T$$

$$\varepsilon_{i,t} = \mu_i + \lambda_t + e_{i,t}, \quad e_{i,t} \sim (0, \sigma_e^2 I)$$

Tab. C-4. Estimate of the effects of GDP per capita on risks associated with governance performance using a cross-country panel data from 1996 to 2011.

Dependent variable: log lending interest rates	
log GDP per capita	-0.430*** (0.017)
Observations	2375
R ²	0.276
Adjusted R ²	0.222
F-statistic	843.1

Note: *** < 0.01, ** < 0.05, and * < 0.1.

For projecting future risk accounting factors, the data of GDP per capita from the SSP database is used. For the reference governance scenario, the GDP per capita trajectory is assumed following SSP2 scenario, while the GDP per capita trajectory is assumed following SSP5 scenario for the strong governance.

C.3 Additional figures and tables

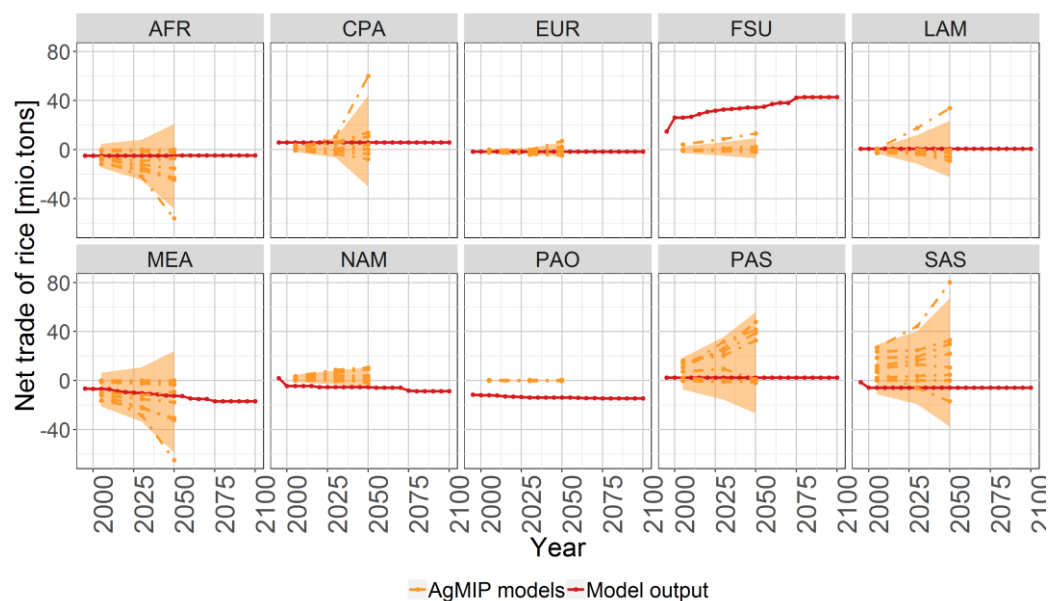


Fig. C-1. Cross-validation of net exports of rice w.r.t. AgMIP model projections in reference scenario. Actual modeled growth rates are represented by red dots and lines, whereas dashed yellow dots and lines are projections from AgMIP models for each simulated time step. Shaded areas depict two times standard deviations from the sample mean of AgMIP model projections.



Fig. C-2. Cross-validation of net exports of oil crops w.r.t. AgMIP model projections in reference scenario. Actual modeled growth rates are represented by red dots and lines, whereas dashed yellow dots and lines are projections from AgMIP models for each simulated time step. Shaded areas depict two times standard deviations from the sample mean of AgMIP model projections.

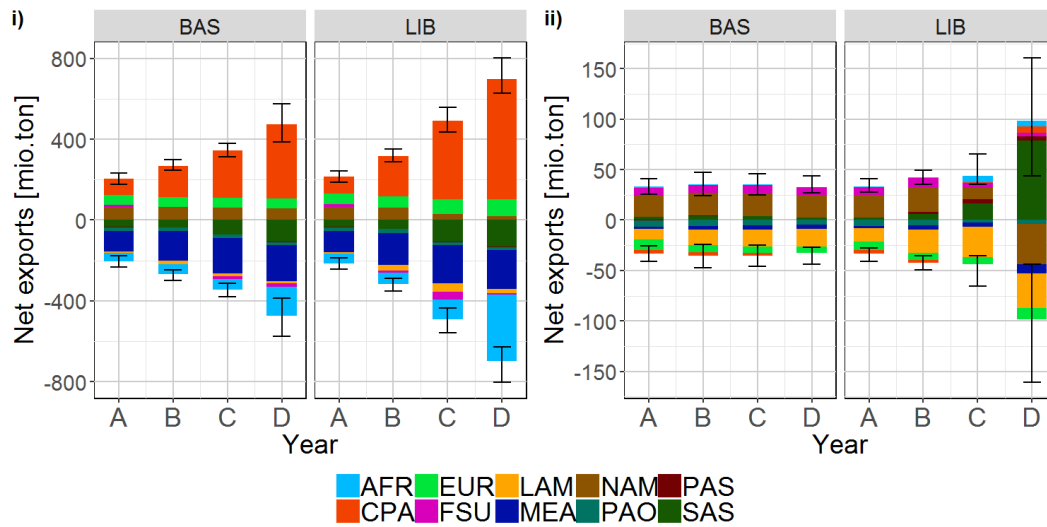


Fig. C-3. Net exports of cereals and oil crops for MAGPIE regions in the two trade scenarios (BAS and LIB) for four time-spans (A = 2005- 2025, B= 2030 – 2050, C = 2055 -2075, D = 2080 -2010) when strong governance scenario is assumed. Panel i refers to the net trade pattern of cereals, while panel ii refers to the net trade patterns of oil crops. The height of bars indicates the averaged net exports across five different GCMs, while the error bars refer to two times standard deviations from the sample mean of global net exports and global net imports.

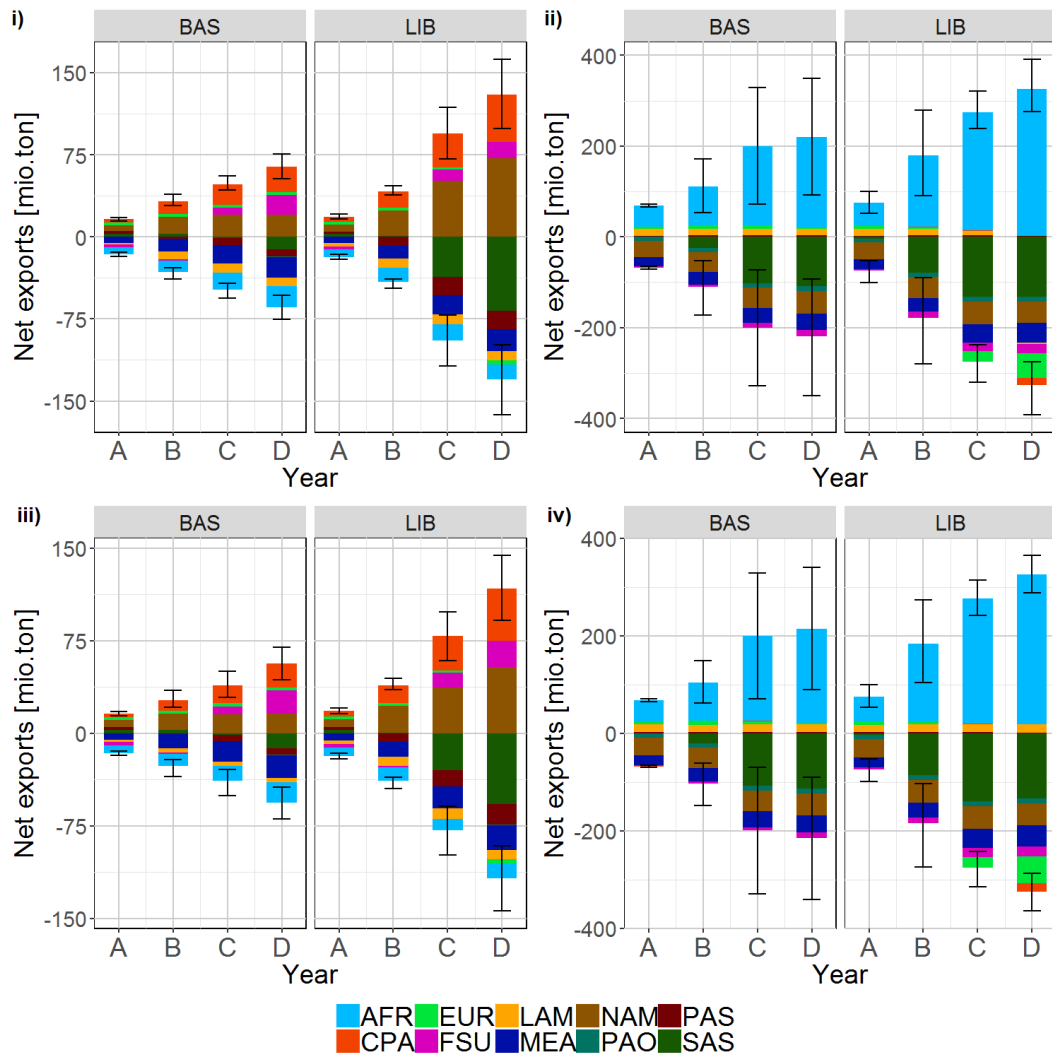


Fig. C-4. Net exports of livestock products and sugar crops for MAGPIE regions in the two trade scenarios (BAS and LIB) for four time-spans (A = 2005- 2025, B= 2030 – 2050, C = 2055 -2075, D = 2080 -2010), when reference governance scenario is assumed. Panels i and iii refer to the net trade pattern of livestock products in the reference and strong governance scenarios, respectively. Panels ii and iv refer to the net trade patterns of sugar crops in the reference and strong governance scenarios, respectively. The height of bars indicates the averaged net exports across five different GCMs, while the error bars refer to two times standard deviations from the sample mean of global net exports and global net imports.

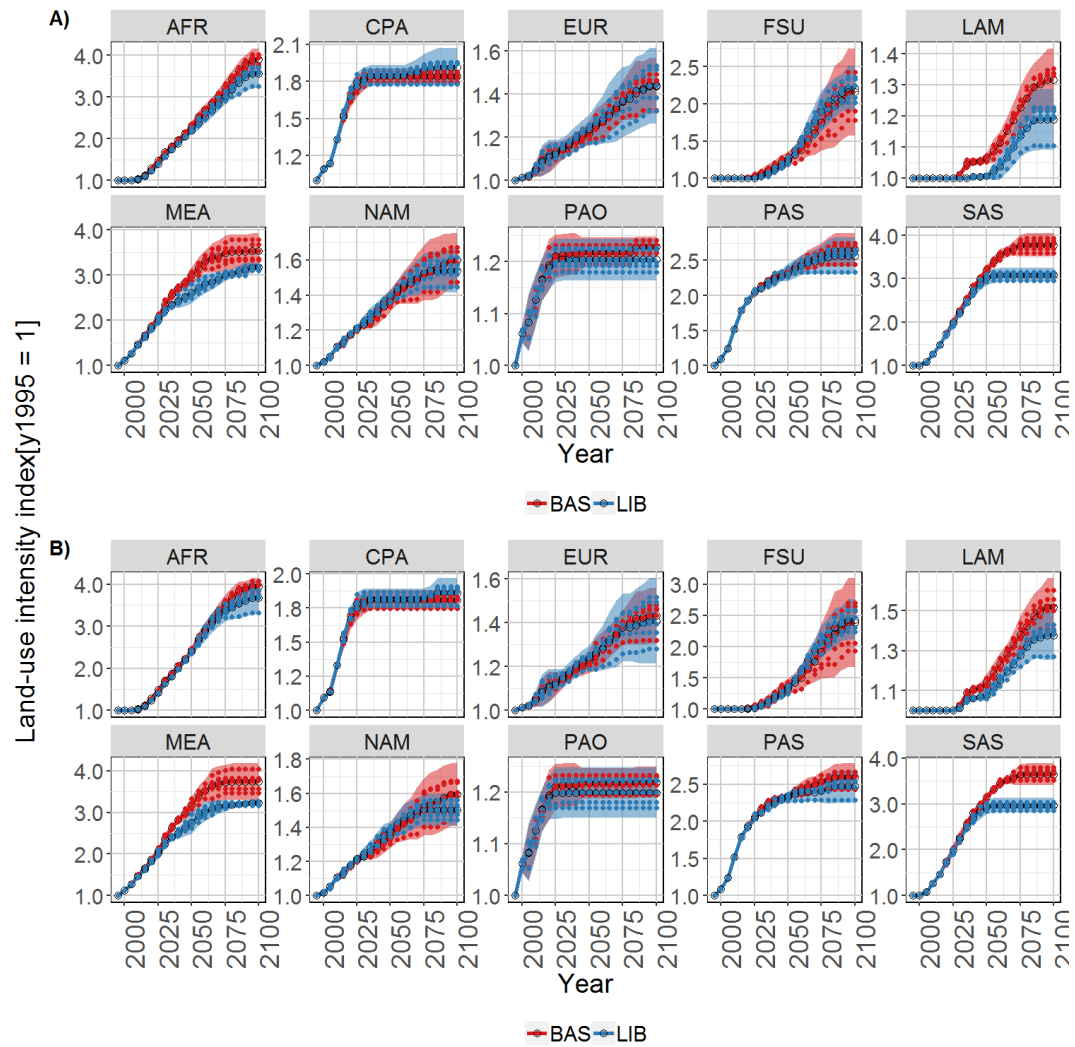


Fig. C-5. Regional land-use intensity in the different scenarios of trade liberalization and governance performance. Panel A refers to the model result when the reference governance scenario is assumed, while panel B is the model results under the strong governance scenario. For each of the five GCMs used in the analysis, actual simulated land-use intensity index is indicated by dots, while solid lines for each panel refer to the mean with respect to different trade scenarios (BAS and LIB). The shaded areas depict two standard deviations from the sample mean across the GCMs for each trade scenario.

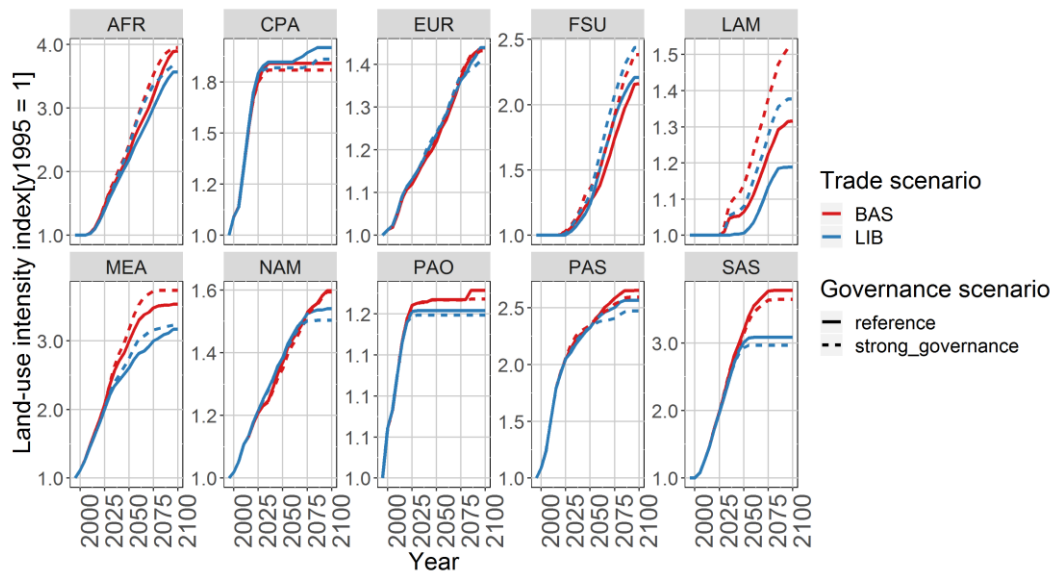


Fig. C-6. Regional land-use intensity in different trade scenarios and governance scenarios. The values are averaged across the five GCMs.

Tab. C-5. Changes of global cropland area in the trade scenarios of BAS and LIB when the reference governance is assumed.

Scenarios	y2005	y2025	y2050	y2075	y2100
BAS	1494.5	1658.8	1853.2	1948.1	1849.7
LIB	1493.4	1627.6	1800.5	1824.7	1693.4
$\Delta_{\text{BAS-LIB}}$	1.1	31.2	52.7	123.4	156.3

Units: million ha.

Tab. C-6. Changes of global cropland area in the trade scenarios of BAS and LIB when the strong governance is assumed.

Scenarios	y2005	y2025	y2050	y2075	y2100
BAS	1494.5	1659.1	1863.4	1932.1	1835.2
LIB	1493.4	1627.8	1811.4	1799.5	1683.8
$\Delta_{\text{BAS-LIB}}$	1.1	31.4	51.9	132.6	151.4

Units: million ha.

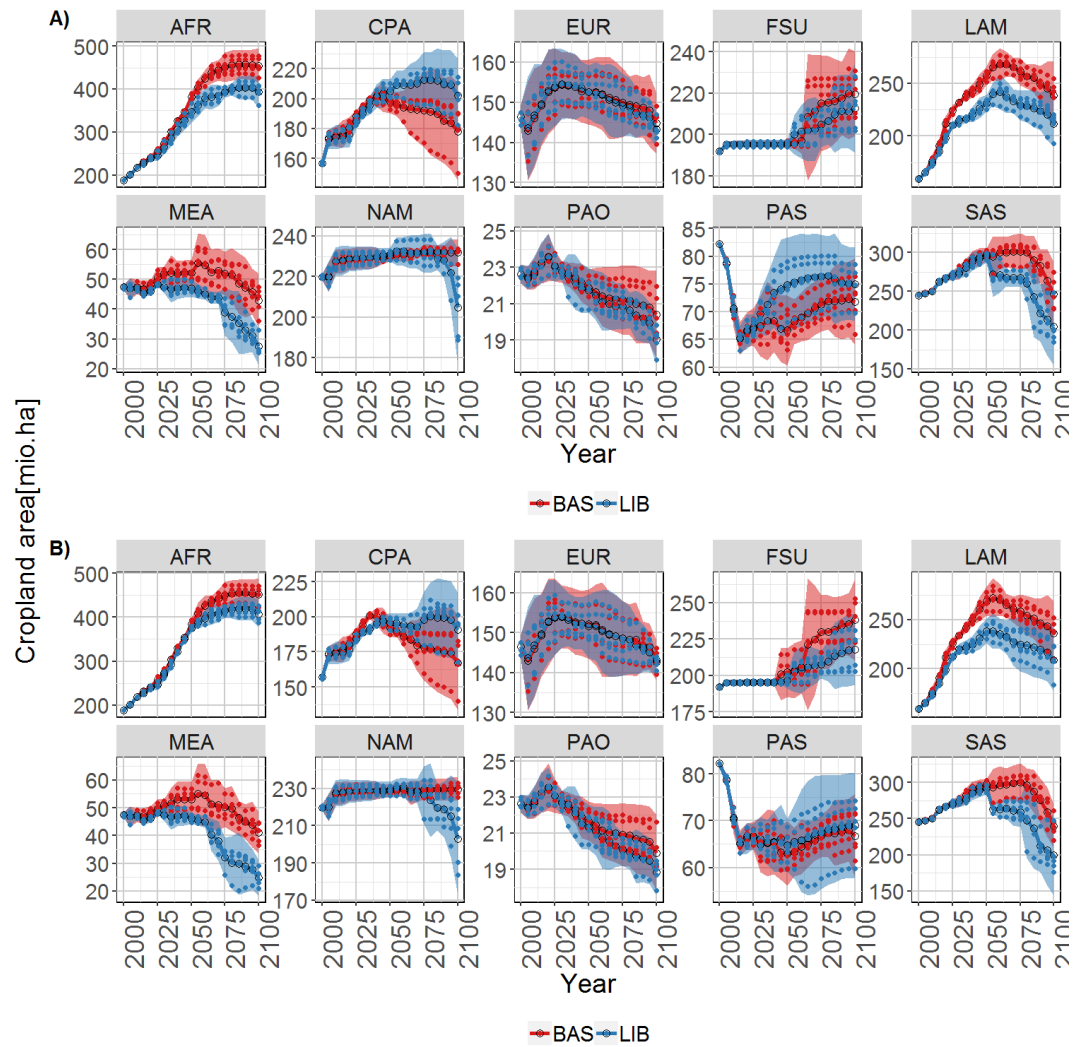


Fig. C-7. Regional cropland area in the different scenarios of trade liberalization and governance performance. Panel A refers to the model result when the reference governance scenario is assumed, while panel B is the model results under the strong governance scenario. For each of the five GCMs used in the analysis, actual simulated cropland area is indicated by dots, while solid lines for each panel refer to the mean. The shaded areas depict two standard deviations from the sample mean across the GCMs.

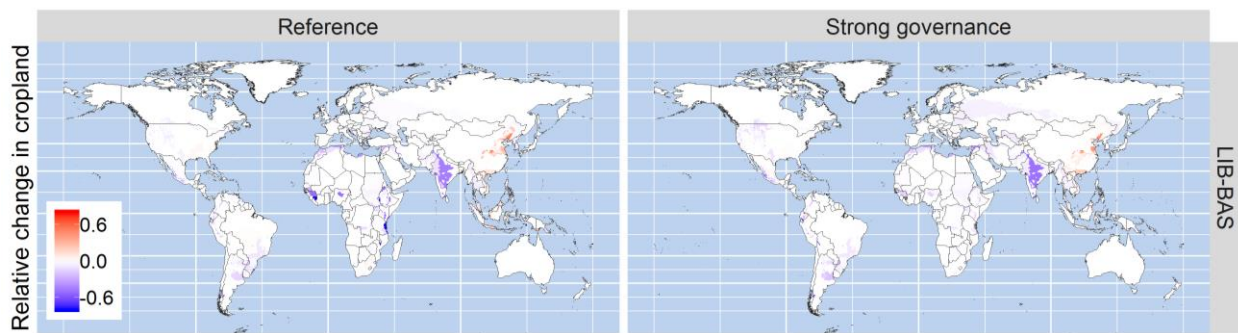


Fig. C-8. Relative change in cropland share due to trade liberalization (LIB - BAS) under different governance scenarios in 2090. The values are averaged across the five GCMs.

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Declaration

I declare that this dissertation, which I submit to the Faculty of Life Science for examination in consideration of the award of a degree (Dr. rer. agr.) is original and represents my own work. I confirm that I completed the dissertation independently based on the stated resources and aids. The contribution of mine and the other authors to the research has been explicated stated and acknowledged in the dissertation. The content of the dissertation has not been submitted or in part for any other degree at the Humboldt University of Berlin or elsewhere.

Xiaoxi Wang

Berlin, November 2018

Tools and Resources

The following software and tools are used for conducting the research and preparing the manuscript for this dissertation.

Modeling: The MAgPIE model is written in Generalized Algebraic Modelling System (GAMS) programming language. The CONOPT3 numerical solver is used to solve the optimization problem. The BARON numerical solver is used to solve the bi-level programming problem for the experiment of the bilateral trade calibration.

Code management: The versioning and revision control system software including Subversion and Git as well as Gitlab repository are used to manage the MAgPIE GAMS code and the R scripts for data processing and start-runs.

Typesetting: The dissertation is written and edited in Microsoft Word 2013, LaTeX, and Adobe Acrobat X Pro. Pandoc is used to convert tex files to docx files.

Citation management: Zotero software is used for generating the bibliography in the dissertation.